Design of Reverse Logistics Network for Waste Batteries with an Application in Turkey

by

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ABSTRACT

Reverse logistics has received increasing attention in the last decade. This is mainly due to the environmental concerns, forcing legislations, and potential economic benefits. Ever increasing amount of waste batteries which are classified as hazardous waste poses a significant environmental problem; thus it requires an effective management.

In this thesis, we develop a mixed-integer linear programming model (MILP) to design reverse logistics network for waste batteries and implemented the model to the Turkey case. The proposed model has various realistic features compared to existing models; it is a multi-period optimization model that considers various battery-types, different capacity options, capacity expansion of facilities, sale prices of recycled materials, variable operational cost, construction cost, and existing infrastructure of the facilities in the network. There are two disposal options for waste batteries: recycling and landfill. Using the developed optimization, the policy makers responsible for the design and operation of the reverse network of waste batteries can decide on the network configuration, while maximizing the profit.

Uncertainty in the return of waste batteries is a major issue in the reverse logistics network design. As the network design requires high investment costs, the uncertainty has to be taken into account. In addition to the deterministic network optimization model, a stochastic programming approach is presented by adding scenarios to consider the uncertain amounts of waste battery returns explicitly. All models are programmed and implemented in GAMS (General Algebraic Modeling System) optimization package and solved using the CPLEX solver.

Finally, we conduct sensitivity analyses to determine which parameters are critical for the network structure and to analyze the impact of variations in the critical parameters.

ÖZET

Çevresel, yasal ve ekonomik nedenlerle son yıllarda tersine lojistik konusuna hem endüstri hem de akademi çevrelerinden giderek artan bir ilgi gözlenmektedir. Bilindiği gibi atık piller tehlikeli atıklar sınıfındadır ve artan miktardaki atık piller, bünyesinde barındırdıkları ağır metaller sebebiyle, çevre için tehdit oluşturmaktadır. Dolayısıyla atık pillerin çevre ve insan sağlığı açısından uygun bertarafının ve geri kazanımının sağlanması gerekmektedir.

Bu çalışmada atık pillerin tersine lojistik ağ tasarımı planlanmış ve karma tamsayılı programlama kullanılarak modellenmiştir. Geliştirdiğimiz model literatürdeki modellerle karşılaştırıldığında birçok realistik özellik barındırmaktadır. Sunduğumuz optimizasyon modeli çok dönemli olup, farklı pil tipleri için 2 farklı bertaraf seçeneği ele almaktadır. Toplanan atık piller tiplerine göre ayrıştırıldıktan sonra ya geri dönüşüm tesisine gönderilerek geri kazanılır ya da bir atık gömme sahasında bertaraf edilir. Ayrıca model farklı kapasite seçenekleri, tesisler için kapasite artırım opsiyonu, geri kazanılan metallerin ikinci el piyasaya satılması, tesisler için sabit ve değişken maliyetleri barındıran bir sistem oluşturmaktadır.

Bilindiği gibi tersine lojistik sistemlerinin yapısında birçok belirsizlik bulunmaktadır. Yüksek yatırım maliyeti gerektiren bu sistemler planlanırken belirsizlikleri göz önünde bulundurmak son derece önemlidir. Bu nedenle yukarıda açıklanan deterministik optimizasyon modeline ek olarak stokastik programlama yaklaşımıyla yeni bir model kurulmuştur. Toplanan pil miktarları için farklı senaryolar kullanılarak stokastik modele denk olan deterministik model elde edilmiştir. Geliştirilen modellerin çözümü için GAMS-CPLEX kullanılmıştır.

Son olarak hangi parametrelerin ağ tasarımında kritik olduğunu saptamak ve kritik parametrelerdeki değişimin ağ tasarımına etkisini ölçmek için duyarlılık analizi yapılmıştır.

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NOMENCLATURE

Sets

T set of time periods,

I set of waste battery collection nodes,

J_E set of pre-established battery sorting facilities,

J_N set of potential locations for sorting facilities, ($J_E \cup J_N = J$)

L_E set of landfill areas pre-established facilities,

L_N set of potential landfill areas, ($L_E \cup L_N = L$)

R set of potential locations for recycling facilities,

B set of battery-types,

M set of recycled material types,

K set of potential technological features,

C set of capacity extension modules,

Q set of capacity options for sorting facilities

Decision Variables

$x1_{ijt}$ amount of mixed batteries transported from the collection node $i \in I$ to the battery sorting facility $j \in J$ at time period $t \in T$,

$x2_{jbrt}$ amount of battery-type $b \in B$ transported from sorting facility $j \in J$ to recycling plant $r \in R$ at time period $t \in T$,

$x3_{jblt}$ amount of battery-type $b \in B$ transported from the sorting facility $j \in J$ to landfill area $l \in L$ at time period $t \in T$,

R_{brt} amount of battery-type $b \in B$, recycled at recycling facility $r \in R$ at time period $t \in T$,

Inv_{mrt} amount of recycled material inventory $m \in M$ at recycling facility $r \in R$ at time period $t \in T$,

$N1_{mrt}$ amount of recycled material $m \in M$ sold from recycling facility $r \in R$ at time period $t \in T$,

$N2_{rlt}$ amount of waste residue transported from recycling facility $r \in R$ to landfill area $l \in L$ at time period $t \in T$,

$z1_{jbt}$ amount of battery-type $b \in B$ processed at the sorting facility $j \in J$ at time period $t \in T$,

ys_{jqt} 1 if a sorting facility with capacity option $q \in Q$ is operational at potential location $j \in J$ at time period $t \in T$, 0 else

us_{jct} 1 if capacity expansion option $c \in C$ is added to sorting facility $j \in J$ at time period $t \in T$, 0 else

yr_{rt} 1 if battery recycling facility $r \in R$ is operational at time period $t \in T$, 0 else

ro_{rt} 1 if battery recycling facility $r \in R$ is built at time period $t \in T$, 0 else

yt_{krt} 1 if recycling technology $k \in K$ is operational at recycling facility $r \in R$ at time $t \in T$, 0 else

yl_{lt} 1 if landfill area $l \in L$ is operational at time period $t \in T$, 0 else

b_{brt} 1 if battery-type $b \in B$ can be processed at recycling facility $r \in R$ at time $t \in T$, 0 else

Parameters

a_{it} amount of battery collected at source $i \in I$ during time period $t \in T$,

$d1_{ij}$ distance between collection node $i \in I$ and sorting facility $j \in J$,

$d2_{jr}$ distance between sorting facility $j \in J$ and recycling facility $r \in R$,

$d3_{jl}$ distance between sorting facility $j \in J$ and landfill area $l \in L$,

$d4_{rl}$ distance between recycling facility $r \in R$ and landfill area $l \in L$,

$UCT1_{ijt}$ unit variable cost of transportation between collection point $i \in I$ and sorting facility $j \in J$ at time period $t \in T$,

$UCT2_{jrt}$ unit variable cost of transportation between sorting facility $j \in J$ and recycling facility $r \in R$ at time period $t \in T$,

$UCT3_{jlt}$ unit variable cost of transportation between sorting facility $j \in J$ and landfill area $l \in L$ at time period $t \in T$,

$UCT4_{rlt}$ unit variable cost of transportation between recycling facility $r \in R$ and landfill area $l \in L$ at time period $t \in T$,

CCS_{jqt} construction cost for sorting facility $j \in J$ at time period $t \in T$,

FCS_{jqt} fixed cost for sorting operations at battery sorting facility $j \in J$ during time period $t \in T$,

$FCCS_{ct}$ capacity expansion cost of capacity expansion option $c \in C$ for sorting facilities at time period $t \in T$,

UCS_{jqt} unit variable cost of sorting operations at sorting facility $j \in J$ at time period $t \in T$,

CCR_{rt} construction cost for recycling facility $r \in R$ at time period $t \in T$,

FCT_{kt} cost of installing technology $k \in K$ at time period $t \in T$,

FCR_{rt} fixed cost of operating recycling facility $r \in R$ at time period $t \in T$,

UCR_{rbt} unit variable cost of recycling operations for battery- type $b \in B$ at recycling facility $r \in R$ at time period $t \in T$,

CCL_{lt} construction cost for landfill area $l \in L$ at time period $t \in T$,

FCL_{lt} fixed cost of operating landfill area $l \in L$ at time period $t \in T$,

UCL_{lt} unit variable cost of landfill operations at landfill area $l \in L$ at time period $t \in T$,

UCI_t unit inventory cost for recycled materials at during time period $t \in T$,

CAP_s_q capacity module q for sorting facilities,

CAP_r_r capacity upper bound of recycling facility $r \in R$,

CAP_l_l storage capacity for landfill area $l \in L$,

α_{ib} share of battery-type $b \in B$ at collection node $i \in I$,

p_{bm} percentage of material type $m \in M$ in battery-type $b \in B$,

$\mathrm{Re}\, v_{mt}$ sale price of recycled material $m \in M$ at time period $t \in T$,

tb_{kb} 1 if technology $k \in K$ is able to process battery-type $b \in B$, 0 else

c_c capacity expansion option $c \in C$,

$ParExistCap\_S_j$ capacity upper bound of sorting facility $j \in J$ in the beginning of planning horizon,

$ParExistCap\_L_l$ capacity upper bound of landfill area $l \in L$ in the beginning of planning horizon,

Chapter 1

INTRODUCTION

1.1 Background

Rapidly growing world population and development in economic and social standards increase resource consumption. Hence, generation of waste and disposal rates rise steadily which means a loss of material and energy. This reveals a critical necessity for managing the large and ever increasing amount of waste.

Hazardous waste is discarded materials with characteristics that make them potentially harmful to the human health, or to the environment, either immediately or over an extended period of time if improperly treated, stored or disposed of. Hazardous waste includes chemicals, heavy metals, or substances which makes them potentially corrosive, toxic, ignitable, or reactive. Improper disposal of hazardous wastes poses a long-term risk for the human health and for the environment. Waste batteries are considered as hazardous wastes which are certainly more risky compared to non-hazardous wastes. With the shift towards industrialization, the hazardous waste generation continuously escalates and constitutes a significant environmental problem. In this thesis we focus on waste battery management from a reverse logistics perspective.

Waste battery management comprises of the generation, collection, processing, transport and disposal of waste batteries. It is a significant aspect of sustainable development that combines technical, economic, environmental and social issues. Technical aspects of waste battery management deal with planning and implementation of waste management facilities and developing recycling technologies. Disposal of waste batteries at a landfill area has been the most common method of disposal and an important component of waste battery management systems. The landfill areas are potential threat for human health and environment in case of improper design or management. In recent years, with increasing environmental consciousness people do not want to live close to disposal sites. As well as the increasing pressure on landfill area capacities, public opposition complicates finding suitable places for new landfill areas.

From a macroeconomic point of view, a cost-benefit analysis should be conducted including social/environmental benefits and the activity costs. The social/environmental benefits can be summarized as the new job opportunities and the saved costs for emission avoidance. The cost of waste battery management activities are the costs of collection, sorting and recovery and there is a potential income which can be obtained through recycling precious metals.

Waste battery generation patterns are determined by the public and their socio-economic characteristics. A clear perception of the amounts and characteristics of waste generated is a key component for developing a robust and cost-effective waste management system strategy. Thus, the public is a critical actor of the waste battery management system where the success of the system directly depends on public reactions.

Growing concerns about climate change, water, ground and air pollution and exhaustion of raw materials point out the need for protecting the environment and ensuring sustainable development. This has triggered governments to establish environmental legislations to minimize the negative impacts of different waste streams on the environment and human health. These legislations aim to ensure that waste is recovered or disposed of without endangering human health or causing harm to the environment. The main goals are preventing the rise in hazardous waste generation and increasing reuse, recovery and recycling of wastes. Various environmental legislations on waste batteries have been published during the last two decades. Besides technical, economic, environmental and social issues, legislations make waste battery management more complex by putting restrictions on the usage of specified metals such as mercury, cadmium and determining targets for collection/recycling activities.

1.2 Key Issues for Waste Battery Management

We classified key issues involved in waste battery management as hazardous structure of batteries, legislations, and economic features.

- **Hazardous Nature**

Battery is an electrochemical energy source that converts chemical energy into electricity. Batteries supply energy to electronic devices that we use frequently in our daily life such as cell phones, power radios and toys.

Batteries can be classified under 2 main groups; primary batteries and secondary batteries. Primary batteries cannot be recharged after usage. Most commonly used ones are zinc-carbon, alkaline-manganese, silver oxide and mercury oxide batteries. Secondary batteries can be recharged repeatedly over their lifetime. Commonly used secondary batteries are nickel-cadmium (NiCd), nickel metal hydride (NiMH), and lithium-ion batteries (Li-ion).

Batteries contain hazardous substances such as mercury, cadmium, arsenic, and lead. Thus, landfilling or incineration is risky for the environment and human health. Nowadays tens of millions of batteries are produced each year that contain tons of toxic metals. The toxic metals that leak out from the batteries contaminate soil and water. One AA battery pollutes eight tons of soil and also affects underground waters negatively. In addition, purification of water containing heavy metals and removal of heavy metals from a contaminated soil are hard processes which are costly, time consuming, and need technology.

Due to the increased usage of portable devices as a result of technological developments, every day we use mobile energy more and more. ‘Mobile energy’ is a notion used for components or products that make mobile devices’ operations possible. Batteries are one of the most popular mobile energy providers. Besides hazardous substances that batteries contain, they contain precious metals and other substances that can be reused. Battery recycling may provide economic advantage in re-using these valuable commodities. Without recycling, these precious metals are lost and could end-up in the environment as harmful and risky substances. Batteries contain heavy metals such as lead, mercury, zinc, copper, lithium, nickel, cadmium; among these, mercury, lead and cadmium are the most harmful for both human body and the environment.

Cadmium (Cd)

Cadmium is one of the most dangerous and toxic substances that is mainly used in the steel and plastics industries. Cadmium compounds are widely used in batteries. Cadmium can enter human body through drinking water or breathing and can cause lung diseases, prostate cancer, anemia, tissue damage, and the destruction of the adrenal glands. The World Health Organization (WHO) set the maximum level of cadmium in the drinking water as 0.003 mg/l (3µg/l) in terms of drinking water quality. Also large number of institutes for health such as The U.S. Department of Health and Human Services and The International Agency for Research on Cancer (IARC) determined that cadmium and certain cadmium compounds are probable or suspected carcinogens.

Mercury (Hg)

Mercury and mercury compounds are also very dangerous in terms of human health and environment. Leakage of mercury can be quickly absorbed by skin or respiratory. Mercury exposure cause many problems in human body such as neurological disorders, destruction of central nervous system, cardiomyopathy, pneumonitis and kidney damage.

Lead (Pb)

Lead is another dangerous metal for human health and environment and it enters human body by respiratory, food chain and drinking water. Lead is frequently used in the production of lead acid batteries. Lead in the human body can cause anemia, stomach ache, kidney and brain inflammation, infertility, cancer, and death. According to the World Health Organization (WHO), lead in drinking water should not be more than 0.01 mg/l (10µg/l). The amount of lead shall be written on batteries in accordance with regulations**.**

Arsenic (As)

Arsenic is a chemical element found in nature. Arsenic and its compounds used in pesticides, herbicides, batteries, cables. The main use of arsenic in alloys is in lead acid batteries for automobiles and cell phone batteries also contain arsenic. People can be exposed to arsenic by breathing, touching, eating, eye contact. Elemental arsenic and arsenic compounds are classified as ‘toxic’ and ‘dangerous for the environment’ by European Union under directive 67/548/EEC. The International Agency for Research on Cancer (IARC) and US Environmental Protection Agency (EPA) have both determined that arsenic is carcinogenic to humans.

- **Legislation**

The second key issue in waste battery management is environmental legislations. With the aim of minimizing negative impacts of waste batteries on the environment, legislations have been published in the last two decades. The European Union adopted first Battery

Directive in 1991. Primarily, restrictions put on use of mercury in most batteries by this directive. Although this directive encourages battery collection and recycling, landfilling and incineration as a final disposal did not reduce as expected and the new Battery Directive 2006/66/EC has been published. The quota application is imposed both for collection and recycling of waste batteries and quotas are determined. Waste battery collection rate targets are specified as 25% and 45% of battery sales for 2012 and 2016 respectively. In Europe every country has its own battery collection system and some member states also have national legislations. Europe's leaders in battery collection are determined as Belgium and Netherlands. In USA, many states have regulations in place requiring battery recycling.

In general, all the legislations designate the required characteristics of the waste battery management system. To establish an efficient system, legislations put the main responsibility on battery manufacturers, introduce measures to prohibit the circulation of batteries containing hazardous substances, and contain targets for collection and recycling of batteries. In addition, the legislations have a more significant role as a guide for countries where battery recycling industry have not been established and proper management of waste batteries posing a serious challenge.

- **Economic Features**

Waste management systems are not only beneficial for environment but also they contribute global economy. The main benefits of the system arise from recycling option. Firstly, recycling industry provides jobs and contributes employment rates. Secondly, the recyclable materials can be diverted from the landfill areas and accordingly economic benefits can be produced through the sale of recycled materials.

In hazardous waste management systems, it is impossible to mention environment and economy separately. The transboundary movement of hazardous wastes constitutes a global socio-economic problem. These movements have revealed due to the increased amount of hazardous wastes and rising landfill prices because of public opposition to landfill areas in developed countries. The Basel Convention, an international treaty, is designed to reduce the movements of hazardous wastes which are specifically from developed to less developed countries. Development in recycling industry also helps to handle this global socio-economic problem.

Specificially, for waste battery management the total cost of the system comprises of variable costs (collection points, collection logistics, sorting, transportation, and recycling) and fixed costs (facility construction, public relations and communication, and administration). The collection cost depends on economies of scale and it is obvious that in the start-up phase the collection cost would be higher due to advertising and campaigns. Among the disposal options, recycling is the most expensive one which is more labor intensive. Recycling cost is highly related to the recycling technology used (hydrometallurgic, pyrometallurgic, electrometallurgic), the value of recovered materials and plant size. Experiences indicate that as a general trend, recycling cost have declined over years, mainly for primary portable batteries, as the amount has increased and led to economies of scale. Thus, public is another important driver for waste battery management systems because the amount and composition of returned batteries are determined by public. Public awareness and cooperation with public are the determinants for the success of waste battery management system. Public can significantly contribute the system by minimizing the waste battery generation, rising the collection and using recycled products.

1.3 Reverse Logistics

Reverse logistics is the main tool for the appropriate management of all types of waste. Efficient planning and execution of reverse logistics provides sustainable and profitgenerating strategies. From an environmental point of view, reverse logistics contributes to hazardous waste reduction, alleviation of landfilling, and conservation of raw materials. In addition, despite not being the main goal of reverse logistics, it provides more cost-effective systems.

Logistics network design is commonly recognized as a strategic supply chain issue of prime importance. The location of production facilities, storage concepts, and transportation strategies are major determinants of supply chain performance. Driven by increasing green concerns, forcing environmental legislations, and economical opportunities recovery of products and materials came into prominence. Product recovery activities raise flows back through the supply chain, from end-users to producers. The management of return flows reveals the concept of ‘Reverse Logistics’. Several definitions of reverse logistics have been given by various authors and organizations.

In the beginning of nineties, firstly Stock (1992) and then Kopicki et al. (1993) recognized the ‘Reverse Logistics’. Based on the Council of Logistics Management’s definition of logistics, Rogers and Tibben-Lembke (2001) stated a reverse logistics process definition which is adequately all-encompassing:

“ The process of planning, implementing, and controlling the efficient, cost effective flow of raw materials, in-process inventory, finished goods and related information from the point of consumption to the point of origin for the purpose of recapturing value or proper disposal.(2001)”

Figure 1.1 depicts a typical reverse logistics network structure which is also convenient for the reverse logistics of waste batteries. As a first stage activity, end-of-life products are collected in specified locations for collection. Following that, these products are transferred to facilities for separation and sent accordingly to facilities to be remanufactured, refurbished, repaired or recycled. Finally, these products or materials are re-distributed.

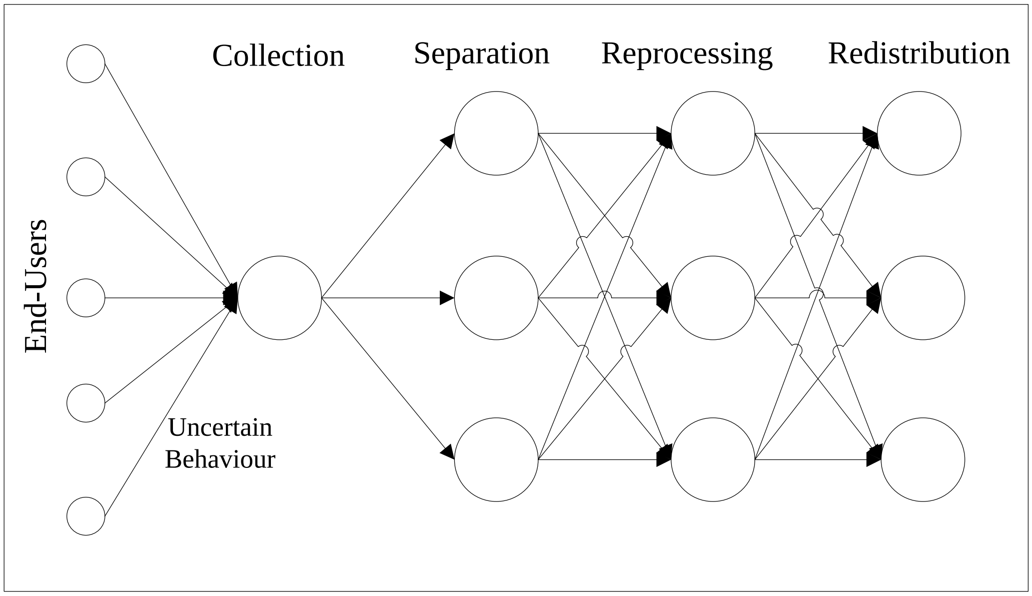


Figure 1.1: A reverse logistics network design

The main differences between reverse networks and forward networks appear in supply stage which is return products in reverse logistics networks. In a classical forward chain, supply is endogenously determined according to system needs. However, in reverse logistics systems supply is exogenously determined and this uncertainty is the main challenge of these types of systems. From a distribution management point of view, forward logistics has one-to-many structure, while reverse logistics has a many-to-one structure. Also, forward network structures do not have a stage such as separation, thus the flow directions are generally known. In contrast, in reverse logistics the returned products' destinations are determined according to the outcomes of the separation process. Finally, another important source of difficulty in reverse logistics systems rises at redistribution stage, due to the fluctuating secondary market prices that depend on various factors.

The interest on reverse logistics systems has increased in the last two decade. The main reason is the necessity of establishing these systems due to environmental concerns and high costs spent in the existing systems.

In this study we developed a decision support tool that can play a significant role in strategic planning the network design of waste batteries which has been motivated by a real situation in Turkey. In the subsequent section, we give the motivation details.

1.4 Motivation

Turkey tries to develop a sustainable way for waste battery management. In 2004, Turkish Ministry of Environment and Urban Planning published the Regulation on Control of Waste Batteries and Accumulators (APAK, 2004).

The main objectives of this regulation are to

- ensure the production of batteries and accumulators considering certain criteria and features
- prevent disposals that damage human health and environment
- control the quantity of hazardous ingredients batteries contain
- establish an efficient waste battery management system

With the aim of environmentally-friendly management of waste batteries, the Turkish Ministry of Environment and Urban Planning enforced the quota application to provide the collection and proper disposal of waste batteries. This regulation holds the manufacturers responsible for collecting waste batteries.

In Turkey, TAP (Portable Battery Manufacturers and Importers Association) is the only institution authorized for collection, transportation, storage, and disposal of waste batteries. It was founded in 2004 and authorized by Ministry of Environment and Urban Planning. TAP collects waste batteries on behalf of manufacturers and importers who are responsible for the collection, transportation, and proper disposal of waste batteries to resolve or decrease environmental degradation.

TAP has over 5,000 collection points across the country in schools, universities, supermarkets, retail battery vendors, hospitals, pharmacies, municipalities, public institutions and organizations. To raise the awareness of public about waste batteries, TAP organizes educational campaigns in schools, publicity campaigns, events, conferences, advertisements. The public is informed about the types of batteries and areas of usage, damage that waste batteries cause and the collection system.

During the last 5 years, the waste battery collection level rose from 3 to 6.03 grams per inhabitant (approximately doubling the collected amounts). There is a considerable increase in battery collection; however, this is still far below from the targets that were aimed with the legislation. In 2011, only ~4.5% of the batteries was collected in Turkey while the target set by “Battery Directive” of EU is 25% for 2012.

In Turkey, on 1 August 2009, the project *Development of Waste Battery Disposal and Recycling Technologies* has started. Within the scope of the project, a battery recycling facility will be established, appropriate recycling technologies will be determined and a system to provide proper disposal of waste batteries will be developed.

In Europe, approximately 30 battery recycling plants exist. All have different features and are able to recycle different types of batteries. In recent years, member states have developed collection systems to reach the targets in accordance with the Battery Directive and raise the amount of collected batteries year by year. The concurrent closure of the Citron SA Battery Recycling Plant and Valdi Battery Recycling Plant decreased the battery recycling capacity in France. During this period, the battery recycling facilities in Germany worked approximately at full capacity. As the performance of collection systems and public awareness increase, the amount of collected waste batteries is expected to increase in the coming decades. Thus, the need for enlarging the waste battery recycling capacity is obvious. The battery recycling facility to be established in Turkey can disburden capacity related problems.

The strategic planning of a reverse network is a critical factor in the performance of recycling operations. The goal of this study is to develop a realistic decision support tool for reverse logistics network design for the case of waste batteries in Turkey.

1.5 Outline of the Thesis

Following the introduction to waste battery management and reverse logistics in Chapter 1, Chapter 2 provides a review of the literature relevant to reverse logistics. Chapter 3 presents problem definition and the mathematical formulation for the deterministic multi-period MILP model. The extension of the proposed model, taking into account the uncertainty is presented in Chapter 4. A scenario-based approach is used and comparative analysis between scenarios is conducted. Finally, the thesis is concluded with the conclusion and the future directions of the performed study.

Chapter 2

LITERATURE REVIEW

2.1 Overview

Reverse logistics (RL) intrinsically have different characteristics from typical forward logistics. The main challenge in reverse logistics is the unstable quantity and quality of return products which makes transportation routing more complex. Typical forward logistics has been studied in detail from different points of view for a long time. However, there is a research potential and need for reverse logistics systems.

In this chapter, we first reviewed the literature on reverse logistics models and practices. Then, we reported the studies on waste battery management activities from different countries and different perspectives.

2.2 Reverse Logistics Practices

The interest in RL has piqued in the last two decades and a considerable number of research from different points of views have been conducted with the aim of constituting effective and efficient systems for return flows.

An early analysis of reverse logistics conducted by Rogers et al. (1999) and they presented an overview to reverse logistics focusing on managerial issues of RL. In another research, Rogers et al. (2001) indicated that reverse logistics systems require high investment cost and it constitutes a significant portion of total logistics cost. Although estimation of RL cost is difficult, reverse logistics cost varies between 4% and 9.9% of the total logistics costs. Fleischmann et al. (2000) analyzed logistics network design for product recovery. They presented the general characteristics of product recovery networks and compared them with traditional networks. The major difference between these networks is supply uncertainty in product recovery environment which is difficult to forecast. In addition, the large number of supply points in product recovery systems comparing to traditional supply networks are pointed out. The authors determined the common activities appeared in different recovery networks as collection, inspection/separation, re-processing, disposal, and re-distribution. The analogies between product recovery systems and waste disposal systems are discussed. Tibben-Lembke and Rogers (2002) analyzed the differences between forward and reverse logistics in a retail sector. The differences between forward and reverse logistics are given in Table 2.1.

Fleischmann et al. (1997) have provided a review of RL models from different perspectives such as distribution planning, inventory control, and production planning. Fleischmann et al. (2000) also focused on the main points for further research in the context of reverse logistics and suggested seven directions. One of these directions is the use of closed-loop network design which is the integration of forward and reverse flows simultaneously. The authors also pointed out the need for examination of the effects of uncertainty on reverse logistics network design.

Beside the studies that mainly discuss the characteristics of RL systems and the difference between RL systems and forward systems, many authors proposed models for the reverse logistics of products from different industrial sectors such as sand, waste battery, waste electrical and electronic equipment (WEEE), carpet, refrigerator, and paper.

Forward	Reverse
Forecasting relatively straightforward	Forecasting more difficult
One to many transportation	Many to one transportation
Product quality uniform	Product quality not uniform
Destination/routing clear	Destination/routing unclear
Standardized channel	Exception driven
Disposition options clear	Disposition not clear
Pricing relatively uniform	Pricing dependent on many factors
Importance of speed recognized	Speed often not considered a priority
Forward distribution costs closely monitored by accounting systems	Reverse costs less directly visible
Inventory management consistent	Inventory management not consistent
Product lifecycle manageable	Product lifecycle issues more complex
Negotiation between parties straightforward	Negotiation complicated by additional considerations
Marketing methods well-known	Marketing complicated by several factors
Real-time information readily available to track product	Visibility of process less transparent

Table 2.1: Differences in forward and reverse logistics (Tibben-Lembke and Rogers, 2002)

Barros et al. (1998) have proposed an optimization model to determine strategic level decisions for sand recycling from construction waste. The legislation in The Netherlands forces the reduction of sand landfilling to a minimal level, which requires an effective network design for sand recycling. In addition, polluted sand requires to be cleaned before reused and this cleaning process needs high investment cost. In order to establish an efficient and effective system, the authors proposed a two-level capacitated facility location model. They consider a time period of one year. The model is solved using heuristic approach which is based on a linear relaxation strengthened by valid inequalities to generate a lower bound. Lu and Bostel (2007) have also developed a two-level facility location model that is specifically for remanufacturing network design and they considered both forward and reverse flows. In this setting, an algorithm based on lagrangian heuristics is proposed to solve the problem. The authors assume that the product demands and available quantities of used products at the customers are known and deterministic.

Sasikumar et al. (2010) developed a profit-oriented mixed-integer nonlinear programming model (MINLP) for the design of reverse logistics of tire remanufacturing system. The proposed multi-echelon model is solved using LINGO 8.0 optimization solver. Schultmann et al. (2003) designed a closed loop supply chain network for spent batteries in Germany. They used a hybrid approach that combines a reverse-supply network optimization model and a flow sheeting process model.

Recently, following the environmental legislations considerable variations take place in contractual, business and operational practices in various sectors to meet legislative requirements. The variations in the systems raise the complexity of RL networks. Various authors discussed the effects of the legislations in different sectors and some developed optimization models considering these requirements. Triantafyllou et al. (2010) investigated the legislative, contractual and operational practices of five hazardous waste streams; WEEE, mobile phones, waste cooking oil, clinical waste and fluorescent lighting tubes. They also discussed the effects of centralized/decentralized waste collection systems, using local recycling opportunities on transport footprint associated with hazardous waste logistics. Indrianti and Rustikasari (2010) presented a sustainable profit maximization model for reverse logistics in case of battery manufacturing in Indonesia that considers both environmental and economic aspects. They ignored the strategic level decisions such as facility locations and applied the model for the case of Yogyakarta Region. Ponce-Cueto et al. (2011) focused on a different aspect of waste management and proposed a model to determine optimal battery collection points for cost-effective management of resources.

They used a multi-criteria decision tool AHP (Analytic Hierarchy Process) to make comparison between potential collection points. Cruz-Rivera and Ertel (2009) have also focused on collection stage of reverse systems and modelled a deterministic incapacitated facility location problem for end-of-life vehicles (ELV). The solution of this model is accomplished using software called SITATION. Moreover, they presented information about the current Mexican ELV management system and the future trends in ELV generation in Mexico.

Wolfer et al. (2011) discussed the physical configuration of reverse logistics, recovery and disposal of WEEE. They proposed a MILP model for locating processing facilities and transporting waste that are in different recovery levels along the links of the network at minimal cost considering legal developments. Then, they applied the model to a case study on Greater Shanghai Area. Even in this extended study, the proposed formulation is limited to a single period optimization model. Achillas et al. (2010) presented a decision support tool for policy-makers and regulators to optimize reverse logistics network of WEEE. With this aim, they formulated a MILP model taking into account existing infrastructure of collection points and recycling facilities and showed the model applicability by implementing the model for the case of Region of Central Macedonia, Greece. Kannan et al. (2010) developed a close-loop supply chain network design model for lead-acid batteries. The proposed model has a multi-echelon, multi-period, multi-product setting. Genetic algorithm (GA) is used as a solution methodology.

All of the models described above are deterministic and static.

2.2.1 Modeling Uncertainty

It has been accepted that reverse logistics environments are characterized by a high level of uncertainty. This uncertainty arises from various sources and put burdens on the performance of RL systems. Several authors investigated uncertainty in reverse systems.

They used different modeling techniques to consider uncertainty in RL systems; such as MILP models with exact algorithms, decomposition algorithms and heuristics algorithms, dynamic problems solved by mixed integer non-linear programming (MINLP) model with heuristics algorithms, scenario-based approaches, sensitivity analyses or simulation.

Alternative scenarios are highly used in covering uncertainty by the reviewed studies. Shih (2001) developed a mixed integer programming model to create an optimal disposition management system for end-of-life computers/home appliances and implemented the model to northern Taiwan case. The model assists to determine the location for storage and treatment facilities. The difficulty of estimating uncertain model parameters are discussed and the methods used for estimating each parameter are given. Finally, the effects of different take-back rates are analyzed via various scenarios. This model has also a single-period formulation. Realff et al. (2004) have presented a multi-period MILP model for carpet recycling network design. The model tries to offer a robust solution; hence the authors take the major sources of uncertainty in this context into account which are the volumes of carpet collected and price of recycled materials. With this aim, a set of alternative scenarios, identified by domain experts, are analyzed and a near optimal solution is provided. Salema et al. (2007) developed a capacitated multi-product reverse distribution network model and implemented the model to real case data of an Iberian company. They also take into account uncertainty in demand/return flows via scenario based approach. Listes and Dekker (2005) pointed out the uncertain characteristic of product recovery networks and developed a stochastic programming based approach. They used scenarios to reflect uncertainty. In another research, Listes (2007) presented a stochastic model for the design of a closed-loop supply chain. They described a decomposition approach for solving the model based on the branch-and-cut method.

Srivastava (2008) developed a model for simultaneous location-allocation of facilities to design a cost effective and efficient RL network. The model determines the disposition decision for various grades of different products with location-allocation and capacity decisions for facilities by using an MILP formulation. Hierarchical optimization is used for various scenarios to offer useful outputs. Fleischmann et al. (2000) analyzed logistics network for product recovery and presented a generic facility location model. The authors discussed the impact of product recovery on logistics network design. They implement the model to two cases; copier remanufacturing and paper recycling and conducted parametric analyses. The authors concluded that the effect of product recovery is very much context dependent. There are various cases in which product recovery flows can be efficiently integrated in existing logistics structure, while in some cases the redesign of logistics network in an integral way is required.

El-Sayed et al. (2010) developed a multi-period, multi-echelon stochastic model for a generic closed-loop network assuming that demand is uncertain. They analyzed the effects of variations in the mean of the demand and the return ratio. Pishvaee et al. (2011) proposed a deterministic MILP model for a closed-loop supply chain network. Then, they presented the robust counterpart of the model considering uncertainty in the quantity of returned products, the demands of second market and the transportation costs.

Using simulation approach is not so common in the reverse logistics context and just a few simulation models were presented to investigate the impact of various uncertain parameters. The simulation approach tries to determine which design variables are more important for a reverse logistics network design. Biehl et al. (2007) evaluated possible reverse logistics systems having regard to a memorandum which aims to divert a significant proportion of used carpets from landfills. They analyzed the effects of different parameters on reverse logistics system using a simulation approach. As a result of the analyses, the authors pointed out the need for collection centers to increase collection of used products. In addition, investment in recycling technology or R&D adds more value to the system comparing to an investment in IT technology. Kara et al. (2007) mentioned the product take-back legislations and accordingly indicated the need of an efficient collection system for end-of-life products. The authors also presented a simulation model to design a collection network for end-of-life electrical appliances with high degree of uncertainty in quality and quantity. The model is implemented for Sydney Metropolitan Area. These two papers investigated different potential design variables and both took some realistic characteristics of RL networks into account. Furthermore, the model proposed by Biehl et al. (2007) has also a closed-loop setting while the model of Kara et al. (2007) has considered only reverse side.

As real-life problems have more than one objective which are generally conflicting, several authors used multi-objective optimization models to design more realistic RL network. Overall, the main objectives in a reverse logistics context are cost and environmental requirements. Krikke et al. (2003) used a multiple objective optimization model and implemented the model to a real case application for refrigerators. In this study, the authors took the environmental regulations into account and aimed to minimize total economic costs, energy usage and residual waste. The authors used multi-criteria optimization, balancing conflicting objectives via balancing coefficients for each objective. Lashkari et al. (2008) proposed a closed loop supply chain network design model in the context of lead-acid battery industry. The model has a multi objective formulation which tries to minimize total cost of operations as well as pollution emissions related to transportation as a secondary objective. The trade-offs between these two objectives are also discussed. Pati et al. (2008) proposed a mixed integer goal programming model (MIGP) to design paper recycling logistics network. Three objectives of this study are reduction in reverse logistics cost; product quality improvement through increased segregation at the source; and environmental benefits through increased waste paper recovery. The model also analyzes the interrelationship between the objectives. The authors concluded that recycling should be encouraged with the aim of reducing the load of wastes on environment.

2.3 Waste Battery Returns

With the general increase of environmental consciousness, in order to minimize the negative impacts of waste batteries on the environment, environmental legislations have been enacted in the last two decades. Common aim of these legislations is to improve concord of batteries with the environment.

There have been literatures reported on collection aspects and processing technologies of batteries recycling. Some studies, focused on the legislations of different countries that have made to improve waste battery management and made comparisons between different battery management systems in different countries over the world. The effectiveness of enforcement of environmental legislations also declared in these studies.

In a typical study of this type, Bernardes et al. (2003) represented the waste battery management systems applied in Europe and USA comparing with the Brazilian situation. This study declared the significance of environmental legislations and their effects on recycling. They also gave practical examples and made suggestions in order to assist to the development of waste battery management system. Espinosa et al. (2004) is also presented Brazilian policy on battery disposal and focused on separate collection of waste batteries and public awareness. Aktaş et al. (2004) presented the situation of waste batteries in Turkey with a short discussion. This study published before the Turkish Legislation on waste batteries was published and before Portable Battery Manufacturers and Importers Association was authorized for waste battery collection. Hence, they only pointed out the significance of public awareness in waste battery management. Another paper focused specifically on Polish waste battery management system and the Polish legislation. In this study, Rogulski and Czerwinski (2006) took a different approach by arguing the feasibility of the collection and recycling level targets that have been determined by national Polish laws. Various study on batteries emphasized efficient recycling technologies and life cycle assessment of batteries. Bernardes et al. (2004) reviewed technologies involved in the collection, sorting, and processing of portable batteries. They discussed four different alternatives as the final disposition of waste batteries that are landfill, stabilization, incineration, and recycling.

Chapter 3

PROBLEM DESCRIPTION AND MODELING

3.1 Introduction

The implementation of waste battery management system requires establishing an appropriate logistics infrastructure. As in the traditional logistics systems, facility locations and system strategies are the major determinants of reverse logistics system performance. We propose a multi-period mixed integer linear programming model (MILP) for the reverse logistics network design of waste batteries and implemented the model to the Turkey case. The network consists of multiple plants which are collection points, sorting facilities, recycling facilities and landfill areas. We consider two disposal options for waste batteries: recycling and landfilling. The developed model addresses many realistic features, such as a multi-period setting, different levels of capacity options, and capacity expansion decisions for sorting facilities, sale of recycled materials, variable operational costs, and a profit-oriented objective function. We take into account the existing infrastructure of sorting facilities and landfill areas. Using the model, the policy-makers responsible for the design and operation of the reverse network of waste batteries can decide on the network configuration, while maximizing the profit. In this chapter, the model will be explained in detail, including an explanation of general characteristics and various processes in the network design.

The organization of the chapter is as follows: Section 3.2 represents the network design and characteristics. Section 3.3 explains the mathematical formulation. In Section 3.4, we introduce model description and the parameters in detail. Section 3.5 presents the computational results. In the following section, we perfomed all units discounts for landfill operations and remodeled the mathematical formulation as a second case. Finally, in Section 3.6 we present the results of the second case and discuss the differences between the results of the two cases.

3.2 Network Representation

This section summarizes the reverse logistics network we use, referring to the network structure depicted in Figure 3.1. The network consists of multiple plants with different functions which are a given number of collection points, a finite number of existing and potential sorting facilities, recycling facilities and landfill areas.

Collection points receive mixed waste batteries from end-users. As each battery chemisty requires a different recycling process, all collected waste batteries are transported to a sorting facility where batteries are categorized by their type. Sorted batteries are either transported to a recycling facility or disposed of at a landfill area. Landfill areas are also the final destination for the residual waste that rise after the recycling process. It is noticeable that all facilities have limited capacities. The decisions made at recycling facilities include the recycled material inventory to be held depending on market price of recycled materials over the planning horizon. The revenues are obtained from recycling when the recycled materials are sold to a secondary market.

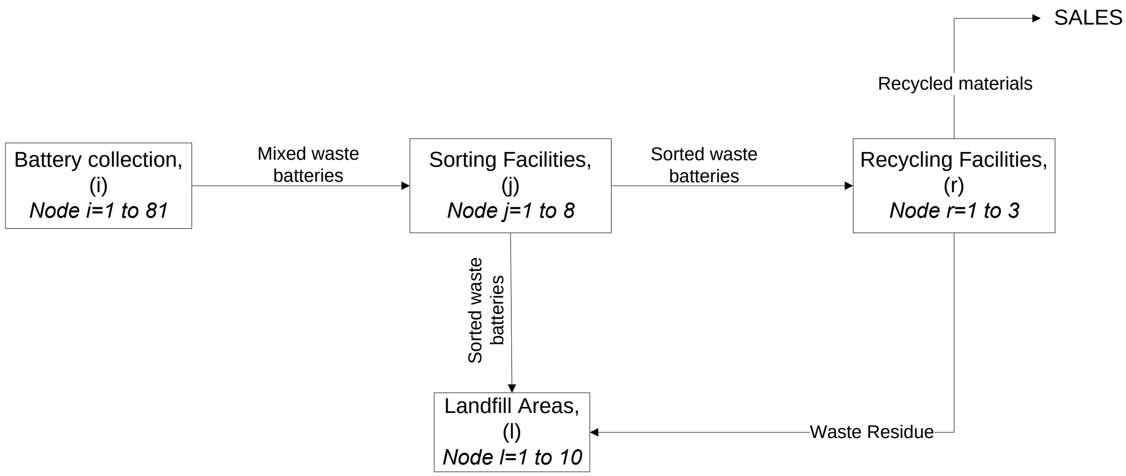


Figure 3.1: Reverse logistics network for waste batteries

In our multi-period setting all decisions are considered over a finite planning horizon. The existing infrastructure of sorting facilities and landfill areas are also considered in the model. In the current situation, sorting of waste batteries is carried out by two companies. Additionally, we considered 6 candidate locations for potential sorting facilities. Waste batteries can be sorted either at an existing/operational facility or at a newly installed one. There is construction cost for newly installed sorting facilities, besides the fixed and variable costs. There are three levels of capacity options for newly installed sorting facilities: low, medium, and high. The capacity expansion decision is also added to the model just for sorting facilities. Existing facilities are assumed to be operational in the initial year. In addition to existing opportunities for sorting activities, there are two existing landfill areas in use with given remaining capacities.

This model answers following questions:

- For each plant type, which set of potential facilities should be opened in each time period?

- When, where and how many sorting facilities to locate choosing which capacity option?
- When to invest for capacity expansion for sorting facilities?
- Which battery types should be recycled in each time period?
- Which technological features should be installed to each recycling facility?
- How much waste battery/residual waste to transport among facility pairs?
- Which amounts of recycled materials should be hold as inventory before sold to a secondary market?

The model has been built upon the following assumptions:

1- The collection points are fixed and the cost of waste battery collection is not included.
2- All the network design decisions are implemented in the beginning of the time periods.
3- Capacity requirements at the collection points are not considered assuming that there are sufficient space for all amounts of returned waste batteries.
4- The collected mixed batteries are directly transferred to a sorting facility. (i.e. keeping inventory at collection points is not possible.)
5- Candidate locations and capacities of potential facilities are known.
6- The demand of the secondary market is unlimited.
7- The system is centralized.
8- All waste batteries collected are suitable for recycling. We did not consider the waste batteries that are damaged and/or non-recyclable.

3.3 The Deterministic Model

The mathematical formulation developed is a multi-period mixed-integer linear programming (MILP) model. The model was programmed and implemented in GAMS (General Algebraic Modeling System) optimization package and solved using the CPLEX solver.

Objective Function

The objective function (3.11) maximizes the total net present value. The incomes in our setting are obtained from the sale of recycled materials to a secondary market which is shown as the first term of the objective function (3.1). The total cost includes the transportation cost, landfilling cost, sorting cost, recycling cost, and inventory holding cost. The transportation cost between the nodes of the network are the multiplication of the distance between each pair of nodes, unit transportation cost and the respective flows. The sorting cost comprises of new facility construction cost, fixed cost, and variable operational cost. The landfilling and recycling costs are formed in an equivalent manner. For sorting cost only, capacity expansion cost are included and for recycling cost only, cost for installation a technological feature is added.

- **Revenue**

$$RM_t = \sum_{m \in M} \sum_{r \in R} \mathrm{Re}\,v_{mt} \times N1_{mrt} \tag{3.1}$$

- **Transportation cost**

$$TC_t = \sum_{i\in I}\sum_{j\in J} d1_{ij} \times x1_{ijt} \times UCT1_{ij} + \sum_{j\in J}\sum_{r\in R}\sum_{b\in B} d2_{jr} \times x2_{jbrt} \times UCT2_{jr} + \sum_{j\in J}\sum_{l\in L}\sum_{b\in B} d3_{jl} \times x3_{jblt} \times UCT3_{jl} + \sum_{r\in R}\sum_{l\in L} d4_{rl} \times N2_{rlt} \times UCT4_{rl} \quad (3.2)$$

- **Sorting cost**

$$SC_t = \sum_{i\in I}\sum_{j\in J}\sum_{q\in Q} USC_{jqt} \times x1_{ijt} \times ys_{jqt} + \sum_{j\in J}\sum_{q\in Q} FCS_{jqt} \times ys_{jqt} \sum_{j\in J_N}\sum_{q\in Q} CCS_{jqt} \times \left(ys_{jqt} - ys_{jq,t-1}\right) + \sum_{j\in J}\sum_{c\in C} FCCS_{ct} \times us_{jct} \quad (3.3)$$

Because of the existence of nonlinear term $\sum_{i\in I}\sum_{j\in J}\sum_{q\in Q} USC_{jqt} \times x1_{ijt} \times ys_{jqt}$ in the sorting cost, we define a new variable TS_{jqt} instead of the cross product of $\sum_{i\in I} x1_{ijt} \times ys_{jqt}$.

Thus, linearization of the sorting cost is satisfied. To make sure that putting the new variable will yield the same result as it has in nonlinear form, we add some additional constraints for the new variable TS_{jqt} that is presented in Constraints (3.4)-(3.6):

$$TS_{jqt} \le ys_{jqt} \times M, \quad \forall j \in J, \forall q \in Q, \forall t \in T \quad (3.4)$$

$$TS_{jqt} \ge \sum_{i\in I} x1_{ijt} - \left(1 - ys_{jqt}\right) \times M, \quad \forall j \in J, \forall q \in Q, \forall t \in T \quad (3.5)$$

$$TS_{jqt} \le \sum_{i\in I} x1_{ijt} + \left(1 - ys_{jqt}\right) \times M, \quad \forall j \in J, \forall q \in Q, \forall t \in T \quad (3.6)$$

where M is a sufficiently large parameter of big-M constraints. Thus, our final linear sorting cost function can be represented as below:

$$SC_t = \sum_{j\in J}\sum_{q\in Q} USC_{jqt} \times TS_{jqt} + \sum_{j\in J}\sum_{q\in Q} FCS_{jqt} \times ys_{jqt}$$
$$\sum_{j\in J_N}\sum_{q\in Q} CCS_{jqt} \times \left(ys_{jqt} - ys_{jq,t-1}\right) + \sum_{j\in J}\sum_{c\in C} FCCS_{ct} \times us_{jct} \tag{3.7}$$

- **Recycling cost**

$$RC_t = \sum_{r\in R} CCR_{rt} \times ro_{rt} + \sum_{r\in R} FCR_{rt} \times yr_{rt} + \sum_{b\in B}\sum_{r\in R} UCR_{brt} \times R_{brt} +$$
$$\sum_{k\in K}\sum_{r\in R} FCT_{kt} \times \left(yt_{krt} - yt_{kr,t-1}\right) \tag{3.8}$$

- **Landfill cost**

$$LC_t = \sum_{j\in J}\sum_{b\in B}\sum_{l\in L} UCL_{lt} \times x3_{jblt} + \sum_{r\in R}\sum_{l\in L} UCL_{lt} \times N2_{rlt} +$$
$$\sum_{l\in L_N} CCL_{lt}\left(yl_{lt} - yl_{l,t-1}\right) \tag{3.9}$$

- **Inventory holding cost**

$$IC_t = \sum_{m}\sum_{r} UCI_t \times Inv_{mrt} \tag{3.10}$$

The objective function is as follows:

$$Maximize\ (Z) = \sum_{t \in T} \left(\left(RM_t - TC_t - SC_t - RC_t - LC_t - IC_t \right) \times \frac{1}{(1+r)^t} \right) \tag{3.11}$$

where

r: discount rate

Constraints

Mass Balances

Constraints (3.12)-(3.15) are mass balance constraints. By Constraint (3.12) all batteries collected at collection points are directly transferred to a sorting facility.

$$\sum_{j \in J} x1_{ijt} - a_{it} = 0, \quad \forall i \in I, \forall t \in T \tag{3.12}$$

The amount of sorted battery-types is calculated by using a predetermined parameter α_{ib} which shows the percentage of waste battery types collected in each collection point.

$$\sum_{i \in I} x1_{ijt} \times \alpha_{ib} = z1_{jbt}, \quad \forall j \in J, \forall b \in B, \forall t \in T \tag{3.13}$$

Constraint (3.14) is a flow conservation constraint. By this constraint, the model guarantees that the waste batteries sorted at sorting facilities are either transported to an operational recycling facility or disposed of at a landfill area.

$$z1_{jbt} = \sum_{r \in R} x2_{jbrt} + \sum_{l \in L} x3_{jblt}, \quad \forall j \in J, \forall b \in B, \forall t \in T \tag{3.14}$$

At recycling facilities a certain part of each battery-type can be recovered due to the technological restrictions and the non-recyclable part of waste batteries is transferred to a landfill area to be disposed of properly via Constraint (3.15).

$$\sum_{b\in B} R_{brt} \times \left(1 - \sum_{m\in M} p_{bm}\right) = \sum_{l\in L} N2_{rlt}, \quad \forall r \in R, \forall t \in T \tag{3.15}$$

Inventory Balances

In traditional supply chain systems, inventory is held in order to reach the desired levels of customer satisfaction. In that case, the main reasons of holding inventory are the uncertainty in the demand side, existence of complex production systems, and possible delays. In the reverse logistics network design model, we also considered holding inventory due to the fluctuating secondary market prices of recycled materials.

The inventory balances for the recycled material inventory at recycling facilities are defined by Constraint (3.16).

$$Inv_{mrt} = Inv_{mr,t-1} + \sum_{b\in B} p_{bm} \times R_{brt} - N1_{mrt}, \quad \forall m \in M, \forall r \in R, \forall t \in T \tag{3.16}$$

Constraint (3.17) determines the amount of waste battery recycled in each recycling facility in each time period.

$$R_{brt} = \sum_{j\in J} x2_{jbrt}, \quad \forall b \in B, \forall r \in R, \forall t \in T \tag{3.17}$$

Capacity Limitations

In constraints (3.18) and (3.19) the operational capacities for sorting facilities are given. These constraints limit the amount of waste battery processed at these plants. For potential sorting facilities a set of capacity option is given and model determines capacity of the facility to be established within the given set. Constraint (3.18) assures that at most one capacity option can be chosen for each sorting facility.

$$\sum_{q \in Q} ys_{jqt} \leq 1, \quad \forall j \in J, \forall t \in T \tag{3.18}$$

Capacity expansion decisions are included for sorting facilities and the model is restricted to a discrete number of levels of capacity expansion at sorting facilities in a particular year. Thus, for sorting facilities, the total capacity of a sorting facility becomes the initial capacity and the installed additional capacities over the planning horizon (3.19).

$$\sum_{i \in I} x1_{ijt} \leq \sum_{q \in Q} CAP\_s_q \times ys_{jqt} + \sum_{c \in C} c_c \times us_{jct'}, \quad \forall j \in J, t' \leq t \tag{3.19}$$

Capacity expansions are limited by constraints (3.20) and (3.21). At most one level of additional capacity can be installed in a particular time period and at most three level of additional capacity can be installed along the planning horizon to each sorting facility.

$$\sum_{c \in C} us_{jct} \leq 1, \quad \forall j \in J, \forall t \in T \tag{3.20}$$

$$\sum_{c \in C} \sum_{t \in T} us_{jct} \leq 3, \quad \forall j \in J \tag{3.21}$$

Constraint (3.22) limits the amount of waste battery processed in battery recycling facilities.

$$R_{brt} \leq CAP\_r_{br} \times yr_{rt}, \quad \forall b \in B, \forall r \in R, \forall t \in T \tag{3.22}$$

The model restricts the closure of the facilities, and installed technological features until the end of planning horizon by constraints (3.23)-(3.26), respectively.

$$ys_{jqt} \leq ys_{jq,t+1}, \quad \forall j \in J, \forall q \in Q, t < T \tag{3.23}$$

$$yr_{rt} \leq yr_{r,t+1}, \quad \forall r \in R, t < T \tag{3.24}$$

$$yt_{krt} \leq yt_{kr,t+1}, \quad \forall k \in K, \forall r \in R, t < T \tag{3.25}$$

$$yl_{lt} \leq yl_{l,t+1}, \quad \forall l \in L, t < T \tag{3.26}$$

The landfill areas have cumulative capacity for specified time horizon and model restricts the total amount of waste batteries and residual waste disposed of at a landfill area by Constraints (3.27)-(3.29).

$$\sum_{j \in J} \sum_{b \in B} x3_{jblt} + \sum_{r \in R} N2_{rlt} \leq y_{lt} \times M, \quad \forall l \in L, \forall t \in T \tag{3.27}$$

$$\sum_{j \in J} \sum_{b \in B} \sum_{t \in T} x3_{jblt} + \sum_{r \in R} \sum_{t \in T} N2_{rlt} \leq CAP\_l_l, \quad \forall l \in L_N \tag{3.28}$$

$$\sum_{j \in J} \sum_{b \in B} \sum_{t \in T} x3_{jblt} + \sum_{r \in R} \sum_{t \in T} N2_{rlt} \leq parExistCap\_L_l, \quad \forall l \in L_E \tag{3.29}$$

The capacities of initially operational facilities are given in Constraints (3.30) and (3.31).

$$ys_{jqt} = 1, \quad \forall j \in J_E, q = 1, t = 1 \tag{3.30}$$

$$yl_{lt} = 1, \quad \forall l \in L_E, t = 1 \tag{3.31}$$

Construction Lead Times

As the model is multi-period, we considered construction lead time of one year for recycling facilities (3.32).

$$ro_{r,t-1} = yr_{rt} - yr_{r,t-1}, \quad \forall r \in R, \forall t \in T \tag{3.32}$$

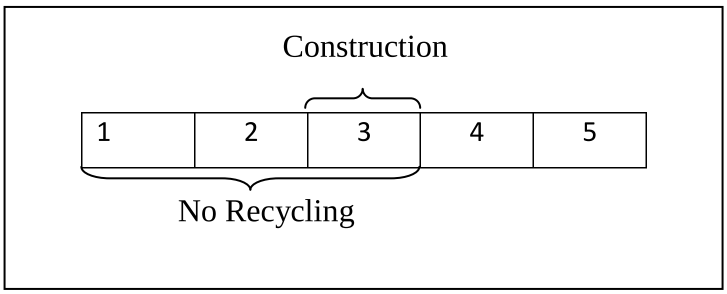


Figure 3.2: Graphical representation of a sample decision

Figure 3.2 represents an example for construction of a new recycling facility. Construction decision is given at the beginning of period 3 and the new recycling facility becomes operational at the beginning of period 4.

Logical Constraints

Constraint (3.33) guarantees that a capacity expansion option can be exercised at a sorting facility only if the facility is operational at that time period.

$$us_{jct} \leq \sum_{q \in Q} ys_{jqt}, \quad \forall j \in J, \forall c \in C, \forall t \in T \tag{3.33}$$

Constraint (3.34) makes sure that a recycling facility must be operational to install a technological feature.

$$yt_{krt} \le yr_{rt}, \quad k \in K, r \in R, t \in T \tag{3.34}$$

These constraints directly show which types of batteries are recycled in which facilities.

$$R_{brt} \le b_{brt} \times M, \quad \forall b \in B, \forall r \in R, \forall t \in T \tag{3.35}$$

In constraint (3.36), we defined technological needs for recycling each type of waste battery. We assume that there are three different technologies, each is able to process zinc-based, nickel-based, and lithium-based batteries, respectively. A two-index matrix is used as input data which restricts the capabilities of technologies. Each row corresponds a technology and each column refers to a battery-type. The value ‘1’ in the matrix shows that the specific technology is able to process the matching battery type. The matrix below is equal to the parameter tb_{kb} .

$$\begin{array}{cc} & b \\ k & \begin{bmatrix} 1 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix} \end{array}$$

$$b_{brt} \le \sum_{k|tb_{kb}=1} yt_{krt}, \quad \forall b \in B, \forall r \in R, \forall t \in T \tag{3.36}$$

Non-negativity and integer constraints

Decision variables for determining facility locations, capacity expansions and installing technological features are assigned as binary variables. Others are set as non-negative variables.

$$x1_{ijt}, x2_{jbrt}, x3_{jblt}, R_{brt}, Inv_{mrt}, N1_{mrt}, N2_{rlt}, z1_{jbt} \geq 0 \tag{3.37}$$

$$ys_{jqt}, yr_{rt}, ro_{rt}, yl_{lt}, yt_{krt}, us_{jct}, b_{brt} \in \{0,1\} \tag{3.38}$$

3.4 Description of the Turkey Case

In this study, we implemented the model to the Turkey Case. The major challenge for reverse logistics planning and solving the proposed model is the uncertainty of the system parameters. This uncertainty is mainly due to the fact that currently the recycling of waste batteries is not practical in Turkey. Most of the parameters are gathered from various sources which will be presented in this section. For the parameters that are not available we used a realistic order-of-magnitude. Our aim is to highlight the features of the model and also to demonstrate its applicability using a commercial solver for instances of a realistic size. We first describe the model parameters in detail and afterwards we present and discuss the results obtained.

It is assumed that waste batteries are collected from 81 collection points located in the center of 81 provinces of Turkey.

To estimate the amount of waste batteries collected at collection points, the data gathered by TAP, is used. The waste battery collection data for Turkey for the time period from 2007 to 2011 is depicted in Figure 3.3. We used the best fit line in order to observe the trend in waste battery collection. The regression equation displayed in the figure is used to estimate the total waste battery collection amount for the planning horizon which is from 2013 to 2022.

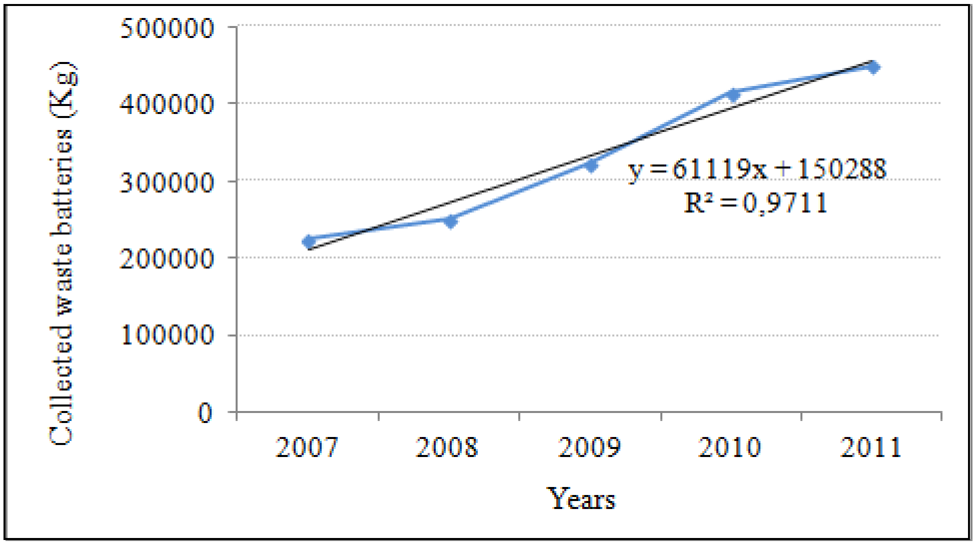


Figure 3.3: The waste battery collection amounts in Turkey, 2007 to 2011, [TAP]

Since we need the waste battey collection amounts for all of the 81 provinces, a new parameter is generated. This parameter indicates the amount of waste battery collection in each province as a percentage of total collection amount and it is assumed to be equal to the percentages of 2011 for the base case. We did some tests with alternative collection amount scenarios that will be presented in Chapter 4. Table 3.1 shows the estimated total waste battery collection amounts in Turkey. The amounts of collected batteries for each province is determined by multiplying the estimated collection amounts with the parameter defined. In Chapter 4, some test are conducted to assess the impact of collection amounts of sources.

Year	Forecasted Collection
2013	578121
2014	639240
2015	700359
2016	761478
2017	822597
2018	883716
2019	944835
2020	1005954
2021	1067073
2022	1128192
2023	1189311

Table 3.1: The forecasted amount of total waste battery collection, from 2013 to 2022

The materials in the content of waste batteries vary by battery-type. The material composition of the batteries we considered (Alkaline, Zinc-carbon, NiCd, NiMH, Li-ion) is given in percentage by weight in the Appendix A. Current technology is able to recycle a certain part of waste batteries. The recoverable metals are zinc, manganese, iron, cupper, cadmium, nickel, cobalt and steel. The revenues for each type of waste battery are determined by considering the revenues obtained from the sale of recycled materials to a secondary market. In general, forecasting scrap metal prices is challenging which highly depends on the demand of metals and changes from region to region. Furthermore, it is harder to predict the long-term fluctuations in scrap metal prices. For the base case, we used double exponential smoothing method to forecast the prices, and used the data published by U.S. Geographical Survey (USGS). As it is not within the scope of this study, we did not assess the performance of our forecast. In Chapter 4, sensitivity analysis will be conducted for observing the effects of variations in scrap metal prices. The results of forecasts are presented in Appendix A. It is assumed that there is a single secondary market with unlimited capacity and the demand of the market is unlimited.

The candidate locations for potential facilities and the locations of existing facilities are depicted in Figure 3.4. As it is mentioned, 81 provinces of Turkey are taken as waste battery collection points. Currently, there are two existing landfill area which are marked with colored circles and two existing sorting facilities marked with colored squares. The remaining shapes represents candidate locations for each type of facility we considered.

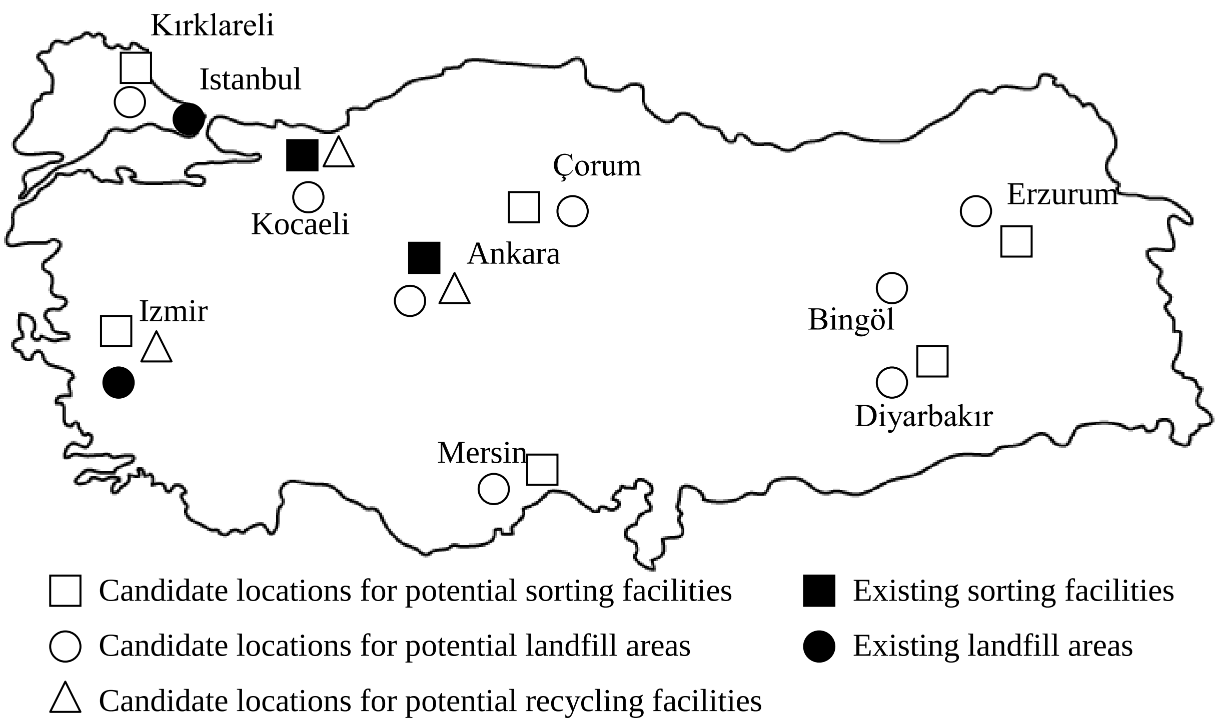


Figure 3.4: Candidate locations for facilities

There are 8 candidate locations for landfill areas and 6 candidate locations for sorting facilities where each of them is located in a different geographical region of Turkey. We considered three levels of capacity for each potential sorting facility which has yearly operating capacities of 200000, 400000 and 500000 kg, respectively. For recycling facilities, we considered 3 candidate locations.

Currently, the cost parameters for potential facilities are not available. In order to determine these parameters in a realistic order-of-magnitude, we used the new investment scheme which divides Turkey into 6 regions. Supporting the lesser developed regions and supporting investments that will create the transfer of technology are within the primary objectives of the investment incentives scheme. The waste disposal activities are within the activities that are going to be supported by the incentive scheme. We defined a coefficient to reflect the relationship between the investement regions of the provinces and the cost parameters. The investment regions are given in Appendix A. Since there are three levels of capacity options for sorting facilities, the cost parameters of sorting facilities are also affected the size of capacities. All parameters related to the capacities and costs are given in the Appendix A.

With increasing green concerns, landfill areas become undesirable and thus the cost for landfill area construction rises. Accordingly, we assumed that the cost of landfill area construction is proportional with population density. In addition to the regional investment coefficient, a parameter is defined in order to indicate the differences on construction cost and fixed cost depending on land prices at candidate locations. For each potential location, this parameter is equal to the ratio of the population of the province to the total population multiplied by a constant.

A distance matrix is generated among the 81 provinces using the data of General Directorate of Highways. The unit transportation cost between the nodes of the network is taken as 0.0037TL/km-kg for the first year of the horizon. All of the cost values except the revenues obtained from recycled materials are assumed to increase by the 5% each year over the planning horizon.

3.5 Application of the proposed model

The goal of this section is to exhibit the computational results of the proposed mathematical model. The model has been solved in GAMS using CPLEX solver which is an optimization software package suitable for solving mixed-integer linear programming problems. All computational work was performed on a personal computer (32-bit operating system, 2.50 GHz CPU, and 4.00 GB). The model statistics are 203967 non-zero elements, 5146 single equations, 14224 single variables, and 876 discrete variables. The objective value is 1249506. Figures 3.5 then shows the location mapping for each type of facility in the optimal solution. The different levels of capacity for sorting facilities are also demonstrated in the Figure 3.5. In addition to the existing facilities, two sorting facilities are constructed with low and high level capacities, and three landfill areas are opened.

As shown in the figure, different types of facilities are located in same provinces. It is due to the transportation cost. Also, we observe that no facility is constructed in eastern, and southeastern regions of anatolia. This is directly related to the insufficient waste battery collection in these regions.

Recycling facility is constructed in Kocaeli, which is located in marmara region. It is an expected solution as Istanbul collects approximately 32% of the total collection in Turkey.

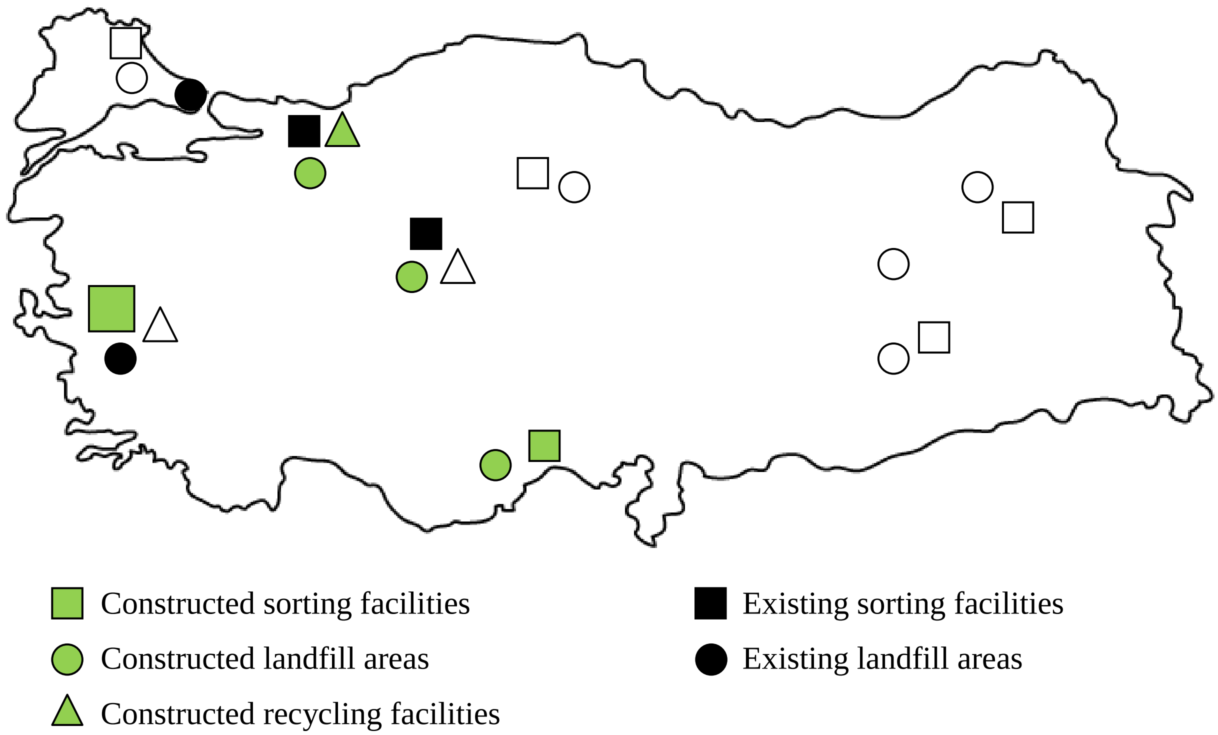


Figure 3.5: Optimal network configuration for the base case

In Figure 3.6, the total cost for each time period in terms of percentages for the transportation cost, sorting cost, landfilling cost, recycling cost, and inventory holding cost are given. As shown in the figure, the major factor which contributes to the total cost is recycling cost. Since the total recycling share over the planning horizon is 89,3% in the optimal solution, it seems to be reasonable. The high cost incur in the initial period is due to the facility constructions. The yearly increase in all costs except inventory holding costs is almost linear. The total cost of activities rise through years as the collection amounts increase.

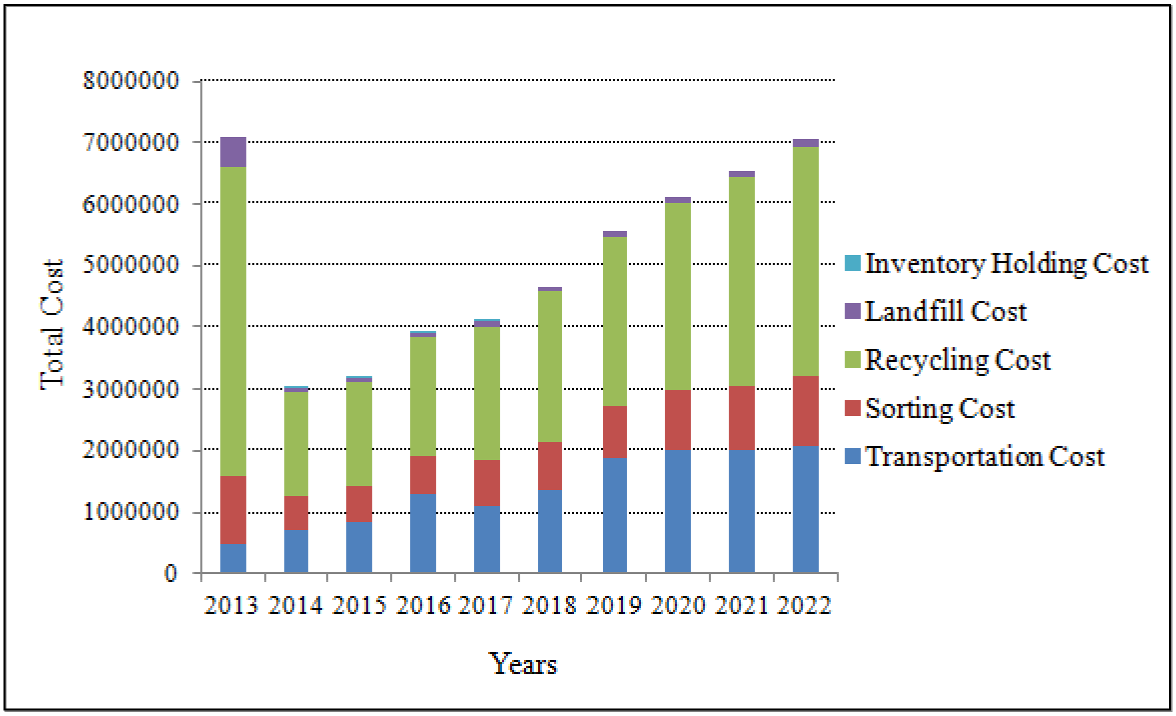


Figure 3.6: Allocation of the total cost in terms of percentages for each period

3.6 All-Unit Discount Cost Function for Landfill Operations

In the model formulation given above we used linear cost function for the landfill operations (3.9). In this section, all-units discount is performed for the variable cost of landfill operations as a second case. The data depicted in Table 3.2 is the current tariff used in Turkey for landfill operations.

Interval	Quantity of waste batteries (tonnes)	Discount rate (%)	Unit cost of disposal (TL/tonne)
1	0–30	0	205
2	31–50	5	194
3	51–70	8	189
4	71–150	10	185
5	151–250	15	174
6	251–500	20	164
7	501 and more	27,5	119

Table 3.2: Discounted costs and associated intervals for landfill operations

All-units discount constitutes a discontinuous piecewise linear function, where exceeding a quantity threshold for a product reveals a reduced cost for each unit. Performing all-units discount in landfill operations can provide incentive to landfill more. To observe the differences occur due to the use of all-units discount instead of linear cost function, we modeled the proposed model with all-units discount for landfill operations.

Let INT be the set of intervals for the discounted costs of landfill operations, $INT = \{1,...,N\}$. The total variable cost of landfill operations is a piecewise linear function of $x3_{jblt}$ which denotes the amount of battery-type $b \in B$ transported from the sorting facility $j \in J$ to landfill area $l \in L$ at time period $t \in T$. Let LC_{lt} be the total variable cost of landfill operations at landfill area $l \in L$ in time period $t \in T$. We used the disjunctive program to model the total variable cost of landfill operations and define the following variables and parameters.

Decision Variables

$land_{l,\mathrm{int},t}$ amount of battery in the range of interval *int* disposed of at landfill area *l* at time period *t*; $\forall l \in L, \forall \mathrm{int} \in INT, \forall t \in T$

$yi_{l,\text{int},t}$ 1 if the amount of battery disposed of at landfill area *l* is in the range of interval *int* at time period *t*, 0 else; $\forall l \in L, \forall \text{int} \in INT, \forall t \in T$

Parameters

$i\_\min_{\text{int}}$ lower bound of interval $\forall \text{int} \in INT$,

$i\_\max_{\text{int}}$ upper bound of interval $\forall \text{int} \in INT$, ($i\_\min_{\text{int}+1} = i\_\max_{\text{int}}$)

$dUCL_{l,\text{int},t}$ unit variable cost of landfill operations at landfill area $\forall l \in L$ and interval $\forall \text{int} \in INT$ at time period $\forall t \in T$,

3.6.1 Disjunctive Program

$$\begin{bmatrix} LC_{lt} = \sum_j \sum_b x3_{jblt} \times dUCL_{l1t} \\ i\_\min_1 \le \sum_j \sum_b x3_{jblt} \le \text{int}\_\max_1 \end{bmatrix} \text{V} \begin{bmatrix} LC_{lt} = \sum_j \sum_b x3_{jblt} \times dUCL_{l2t} \\ i\_\min_2 \le \sum_j \sum_b x3_{jblt} \le \text{int}\_\max_2 \end{bmatrix} \text{V}$$

$$\begin{bmatrix} LC_{lt} = \sum_j \sum_b x3_{jblt} \times dUCL_{l3t} \\ i\_\min_3 \le \sum_j \sum_b x3_{jblt} \le i\_\max_3 \end{bmatrix} \text{V} \begin{bmatrix} LC_{lt} = \sum_j \sum_b x3_{jblt} \times dUCL_{l4t} \\ i\_\min_4 \le \sum_j \sum_b x3_{jblt} \le i\_\max_4 \end{bmatrix} \text{V}$$

$$\begin{bmatrix} LC_{lt} = \sum_j \sum_b x3_{jblt} \times dUCL_{l5t} \\ i\_\min_5 \le \sum_j \sum_b x3_{jblt} \le i\_\max_5 \end{bmatrix} \text{V} \begin{bmatrix} LC_{jt} = \sum_j \sum_b x3_{jblt} \times dUCL_{l6t} \\ i\_\min_6 \le \sum_j \sum_b x3_{jblt} \le i\_\max_6 \end{bmatrix} \text{V}$$

$$\begin{bmatrix} LC_{lt} = \sum_j \sum_b x3_{jblt} \times dUCL_{l7t} \\ i\_\min_7 \le \sum_j \sum_b x3_{jblt} \le i\_\max_7 \end{bmatrix} \quad \forall l \in L, \forall t \in T \tag{3.39}$$

To establish the relation between the amount of waste battery transported to a landfill area at a specific time period and the interval it corresponds, we used the new variable $land_{l,\text{int},t}$.

$$\sum_{i\in J}\sum_{b\in B} x3_{jblt} = \sum_{\text{int}\in INT} land_{l,\text{int},t}, \quad \forall l \in L, \forall t \in T \tag{3.40}$$

As we need to know $\sum_{i\in J}\sum_{b\in B} x3_{jblt}$ corresponds to which interval, we introduced the binary variables $yi_{l,\text{int},t}$ and add Constraint (3.41).

$$\sum_{\text{int}\in INT} yi_{l,\text{int},t} = 1, \quad \forall l \in L, \forall t \in T \tag{3.41}$$

To connect the binary variables to $land_{l,\text{int},t}$, we add Constraint (3.42).

$$\text{int\_min}_{\text{int}} \times yi_{l,\text{int},t} \le land_{l,\text{int},t} \le \text{int\_max}_{\text{int}} \times yi_{l,\text{int},t}, \quad \forall l \in L, \forall \text{int} \in INT, \forall t \in T \tag{3.42}$$

Since the only change in the objective function occurs in the landfill cost, we indicate only new landfill cost in Constraint (3.43). Exactly same constraints (3.12) – (3.38) are used in this model.

- **Landfill Cost**

$$\begin{aligned} LC_t &= \sum_{l\in L_N} CCL_r \left(yl_{lt} - yl_{l,t-1}\right) + \sum_{l\in L_N} FCL_{lt} \times yl_{lt} + \\ &\sum_{r\in R}\sum_{l\in L} UCL_{lt} \times N2_{rlt} + \sum_{\text{int}\in INT}\sum_{l\in L} dUCL_{l,\text{int},t} \times land_{l,\text{int},t} \end{aligned} \tag{3.43}$$

3.7 Computational Results and Discussion

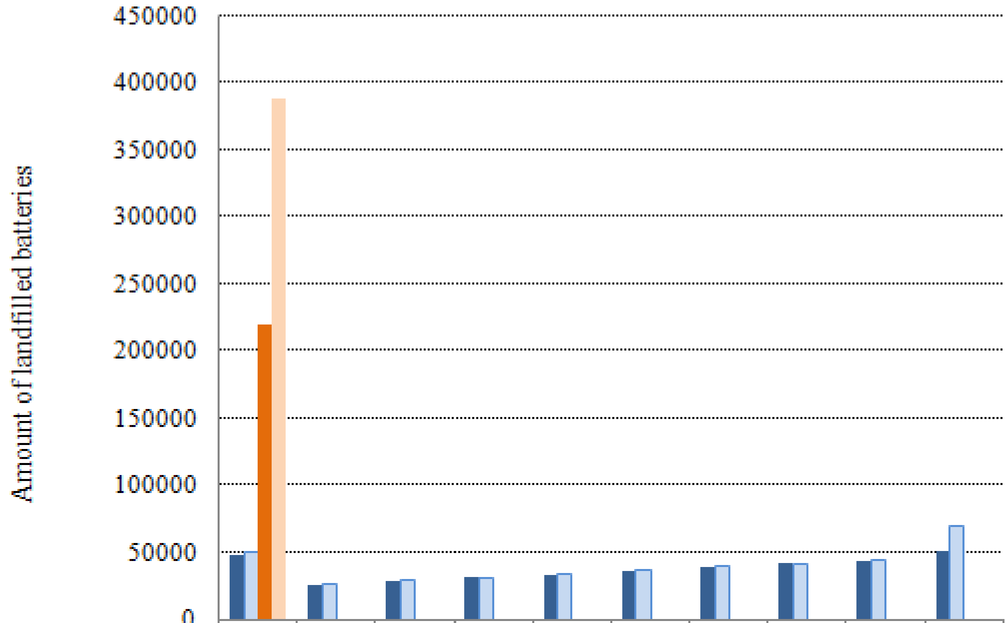
The model statistics using all-units discount for landfill operations are 208707 non-zero elements, 6746 single equations, 15624 single variables, and 1576 discrete variables. The objective value is 1333114 which is 6,7% higher than the objective value obtained in the base case.

Optimal network configuration, obtained using all-units discounts, is exactly same as the optimal network illustrated in Figure 3.5. The Table 3.3 displays the landfilling and recycling ratios of collected waste batteries using the two different cost functions. All-units discounts increased landfilling share by 0,2%. Although the difference between the ratios of the two cases is very small, we can say that as expected the all-unit discount cost function provides incentive to landfill more in our case. However it also depends the discounted costs, intervals, and discount rates. There is another significant observation. Using linear cost function, 5 different landfill areas are used for waste batteries, while using all-units discount only 3 of them are used.

	Linear cost function	All-unit discount cost function
Landfill share (%)	10,7%	10,9%
Recycling share (%)	89,3%	89,1%

Table 3.3: Landfill and recycling shares in the optimal solutions

In both results, landfill areas are opened in the same locations. Figure 3.7 shows the amount of waste battery transferred to the landfill areas in the optimal solutions for the two cases.



	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
Base Case- Mersin	47950	26087	28581	31076	33570	36373	39166	41698	44232	51378
All-Units-Discount- Mersin	50000	26087	28581	31076	33570	36373	39166	41698	44232	70000
Base Case- Ankara	219018									
All-Units Discount- Ankara	388130									

Figure 3.7: Amount of landfilled batteries in the optimal solutions

It is remarkable that 50000 is the lower bound of the 2nd interval for discounted costs. In 2013, using all-units discounts, the model increases the amount of waste battery transferred to the landfill area in Mersin from 47950 to 50000 to reach the next interval. Similarly, in 2022, the waste batteries landfilled in Mersin increased to reach 3rd interval. There is a trade-off between the discounted cost and transportation cost. In that year, discounted cost is more advantageous. Hence, in the optimal solution of the second case, more waste batteries are transferred to the landfill area in Mersin. As expected, we observe that using all-units discounts provides incentive to landfill more. This is an issue that the policy-makers should take into account when determining cost structure of operations.

Chapter 4

MODEL EXTENSION

4.1 Introduction

Supply chain systems are very complex systems that numerous products are produced and transferred between nodes of the network with the objective of satisfying customer demand. However, in most cases customer demand is uncertain and projecting the customer demand accurately is a challenging work. Uncertain demand is the major source of ambiguity in supply chain management. This uncertainty affects supply chain infrastructure significantly. Underestimating uncertainty and its impact causes misleading decisions. Modeling a supply chain network system using complete and deterministic data does not accord with the dynamic nature of these systems and result in inferior decisions comparing to models considered uncertainty. The uncertainty in the supply chain management has been studied in detail by various researcher.

It has been indicated that reverse logistics systems are also characterized by a high level of uncertainty (see e.g. Fleischmann et al., 1997). Due to the varying quality and quantity of used products in reverse logistics systems, these systems are expected to have significantly higher uncertainty compared to traditional forward logistics networks. The major source of vagueness in reverse logistics systems is uncertain return of used products. It is critical to analyze the effects of uncertainty on the network design.

In Chapter 3, we proposed a deterministic model to design reverse logistics network of waste batteries considering all parameters are known. In the following section we discuss the extension of the model considering uncertainty in returns. Next, we represent brief information about two-stage stochastic programming approach. The model formulation considering uncertainty is given. Sensitivity analysis is conducted to observe the effects of variations in critical parameters. Finally, the computational results and the discussion are presented.

4.2 Extension of the model to consider uncertainty

We extend our network design model including uncertainty in the amount of returned waste batteries from various collection points. Since the appropriate method is context-dependent and a single theory cannot be sufficient to model all kinds of uncertainty (Fleischmann et al., 2000), firstly appropriate representation of the uncertainty in our case should be determined.

In the literature, two distinct methodologies are frequently used while addressing uncertainty; distribution-based approach and scenario-based approach. In distribution-based approach random variables with known probability distributions enters to the model as uncertain parameters for handling uncertainty. This approach is appropriate when a set of discrete scenarios cannot be identified. On the other side, in scenario-based approach the uncertainty is modeled as discrete scenarios with given probabilities for different expected outcomes.

We extend our ordinary mixed-integer linear programming (MILP) model by introducing a finite number of independent scenarios to include uncertainty. The literature shows that our context is appropriate for scenario-based approach.

4.2.1 Two-stage Stochastic Programming Approach

One of the most popular frameworks for planning under uncertainty is two-stage stochastic programming with fixed recourse (Birge and Louveaux, 1997) which is a technique that can deal with uncertainty in any one of the model parameters. In this approach, the set of decisions and constraints are divided into two groups. One subset of decisions has to be determined when the related environmental information is not completely available. These decisions are called first-stage variables or design variables and the period, in which these decisions are taken, is called the first-stage. The first-stage decision variables are generally structural decisions. Given the first-stage decisions, the second subset of decisions can be determined based on the realization of a number of random events which are called second-stage decisions. The corresponding variables are called second-stage variables or control variables and the period is second-stage. These 'wait-and-see' recourse decisions model how the decision maker adapts to the unfolding uncertain events. The second-stage variables are generally operational level decisions. The objective is to minimize the sum of first stage costs, which are deterministic and the expectation of second stage costs.

The classical two stage stochastic program with fixed recourse is as follows (Birge and Louveaux, 1997):

$$\begin{aligned} &\min_{x \in R^n} c^T x + E\left[Q(x,\varepsilon)\right] \\ &s.t. \quad Ax = b,\ x \geq 0 \end{aligned} \tag{4.1}$$

where $Q(x,\varepsilon)$ is the optimal value of the second-stage problem and can be stated as:

$$Q(x,\varepsilon) = \min_{y \in R^m} q^T y$$
$$s.t. \quad Tx + Wy = h, \quad y \geq 0 \tag{4.2}$$

The vector x is the first-stage decision variable with an associated cost vector c. Here $\varepsilon := (q,h,T,W)$ are the parameters of the second stage problem given in (4.2). Some or all elements of the vector can be random. We will consider discrete distributions only, which means that vector ε has a finite number of realizations (i.e. scenarios), $\varepsilon_k(q_k, h_k, T_k, W_k)$ with respect to probabilities p_k, $k = 1,..., K$. Thus, we can write:

$$E\left[Q(x,\varepsilon)\right] = \sum_{k=1}^{K} p_k \, Q(x,\varepsilon_k) \tag{4.3}$$

Hence, for a taken first-stage decision x, the expectation $E\left[Q(x,\varepsilon)\right]$ is the optimal value of the linear programming problem given in (4.4):

$$\min_{y_1, y_2, \ldots, y_k} \sum_{k=1}^{K} p_k \, q_k^T y_k$$
$$s.t. \quad T_k x + W_k y = h_k \tag{4.4}$$
$$y_k \geq 0, \quad \forall k$$

Using the Equations (4.3) and (4.4) we can formulate a linear program that forms the deterministic equivalent of the stochastic problem:

$$\begin{aligned}
&\min_{x, y_a, \ldots, y_k} c^T x + \sum_{k=1}^{K} p_k q_k^T y_k \\
&s.t. \quad T_k x + W_k y_k = h_k, \quad \forall k \\
&\qquad\; Ax = b, \\
&\qquad\; x \geq 0,\ y_k \geq 0, \quad \forall k
\end{aligned} \tag{4.5}$$

4.2.2 Model Description

The model proposed in Chapter 3 is extended to consider uncertainty in the waste battery return amounts at the collection points, using the two-stage stochastic programming concept. For the proposed deterministic reverse logistics network design model we classified the decisions as location and logistics decisions to fit into the two-stage stochastic programming framework. The location decisions are the first-stage decisions that determine the locations of facilities while network flow decisions or logistics decisions are categorized as second-stage decisions. The capacity expansions and additional technological features are included to the location decisions. The uncertainty is the amount of collected waste batteries from various collection points. We considered four discrete scenarios one of which is the base case. In Scenario 1, we suppose that the waste battery collection is proportional to the population of the province. For Scenario 2, the average amounts of collected batteries per inhabitant for each province are calculated based on the data of 2011. In this scenario, we assume that the amounts of collected batteries per inhabitant which is below the average rise to the average, while the amounts above the average reach the highest collection per inhabitant. In Scenario 3, we used the quartile of the data set and implement the same logique we used in Scenario 2. T

Case	Description
Base Case	Collection percentages of the provinces are equal to the percentages of 2011
Scenario 1	Collection is proportional to population of each province
Scenario 2	The collection amount of the provinces that collect below average (gr/inhabitant) rise their collection to average, while the provinces that collect above the average reach to the highest collection (gr/inhabitant)
Scenario 3	Quartile of the data set is used. Provinces in each range increases their collection and reaches the next break point

Table 4.1: Desciption of the base case and scenarios

In Appendix A, waste battery collection amounts with respect two the base case and scenarios are depicted. In all scenarios, we change the collection percentages of the provinces where the total collection amount remains same. Thus, there can be a decline in the collection amount of a province compared to base case.

4.2.3 Model Formulation Using Scenario-Based Approach

In addition to the sets described in the deterministic model formulation, we add a new set to define the scenarios considered. This new dimension is also added to some variables and parameters as follows.

The new index is:

s= {1,...,S} scenarios

Parameters:

Same parameters in the deterministic model are used except the parameter a_{it} which represents amount of battery collected at source $i \in I$ during time period $t \in T$. In addition to the predefined parameters we defined a new parameter to indicate the probabilities of scenarios.

a_{sit} amount of battery collected at source *i* during time period *t*, for scenario *s* (kg/year),

P_s probability of scenario s,

Variables:

The new dimension is added to the second-stage decision variables.

$x1_{sijt}$ amount of mixed batteries transported from the collection node *i* to the battery sorting facility *j* at time period *t* in scenario *s*,

$x2_{sjbrt}$ amount of battery- type *b* transported from sorting facility *j* to recycling plant *r* at time period *t* in scenario *s*,

$x3_{sjbrt}$ amount of battery transported from the sorting facility *j* to landfill area *l* at time period *t* in scenario *s*,

R_{sbrt} amount of battery-type *b*, recycled at recycling facility *r* at time period *t* in scenario *s*,

Inv_{smrt} amount of recycled material inventory *m* at recycling facility *r* at time period *t* in scenario *s*,

$N1_{smrt}$ amount of recycled material *m* sold at time period *t* in scenario *s*,

$N2_{srlt}$ amount of waste residue transported from recycling facility *r* to landfill area *l* at time period *t* in scenario *s*,

$z1_{sjbt}$ amount of battery-type *b* processed at the sorting facility *j* at time period *t* in scenario *s*,

- **Revenues**

$$RM_t = \sum_{s \in S} P_s \left(\sum_{m \in M} \sum_{r \in R} \mathrm{Re}\, v_{mt} \times N1_{smrt} \right) \tag{4.6}$$

- **Transportation cost**

$$TC_t = \sum_{s \in S} P_s \left(\begin{array}{l} \sum_{i \in I} \sum_{j \in J} d1_{ij} \times x1_{ijt} \times UCT\,1_{ij} + \sum_{j \in J} \sum_{r \in R} \sum_{b \in B} d\,2_{jr} \times x\,2_{jbrt} \times UCT\;2_{jr} + \\ \sum_{j \in J} \sum_{l \in L} \sum_{b \in B} d\,3_{jl} \times x3_{jblt} \times UCT\;3_{jl} + \sum_{r \in R} \sum_{l \in L} d4_{rl} \times N2_{rlt} \times UCT\;4_{rl} \end{array} \right) \tag{4.7}$$

- **Sorting cost**

$$\begin{aligned} SC_t = & \sum_{s \in S} P_s \left(\sum_{j \in J} \sum_{q \in Q} USC_{jqt} \times TS_{sjqt} \right) + \sum_{j \in J} \sum_{q \in Q} FCS_{jqt} \times ys_{jqt} + \\ & \sum_{j \in J_N} \sum_{q \in Q} CCS_{jqt} \times \left(ys_{jqt} - ys_{jq,t-1} \right) + \sum_{j \in J_N} \sum_{c \in C} FCCS_{ct} \times us_{jct} \end{aligned} \tag{4.8}$$

- **Recycling cost**

$$\begin{aligned} RC_t = & \sum_{r \in R} CCR_{rt} \times ro_{rt} + \sum_{r \in R} FCR_{rt} \times yr_{rt} + \sum_{s \in S} P_s \left(\sum_{b \in B} \sum_{r \in R} UCR_{brt} \times R_{sbrt} \right) + \\ & \sum_{k \in K} \sum_{r \in R} FCT_{kt} \times \left(yt_{krt} - yt_{kr,t-1} \right) \end{aligned} \tag{4.9}$$

- **Landfill cost**

$$LC_t = \sum_{l \in L_N} CCL_{lt}\left(yl_{lt} - yl_{l,t-1}\right) + \sum_{s \in S} P_s \left(\sum_{j \in J} \sum_{b \in \mathbf{B}} \sum_{l \in L} UCL_{lt} \times x3_{sjblt} + \sum_{r \in R} \sum_{l \in L} UCL_{lt} \times N2_{srlt} \right) \tag{4.10}$$

- **Inventory holding cost**

$$IC_t = \sum_{s \in S} P_s \left(\sum_{m} \sum_{r} UCI_t \times Inv_{smrt} \right) \tag{4.11}$$

Objective Function

$$Maximize(Z) = \sum_{t \in T} \left(\left(RM_t - TC_t - SC_t - RC_t - LC_t - IC_t \right) \times \frac{1}{(1+r)^t} \right) \tag{4.12}$$

Constraints

$$\sum_{j \in J} x1_{sijt} - a_{sit} = 0, \quad \forall s \in S, \forall i \in I, \forall t \in T \tag{4.13}$$

$$\sum_{i \in I} x1_{sijt} \times \alpha_{ib} = z1_{sjbt}, \quad \forall s \in S, \forall j \in J, \forall b \in B, \forall t \in T \tag{4.14}$$

$$z1_{sjbt} = \sum_{r \in R} x2_{sjbrt} + \sum_{l \in L} x3_{sjblt}, \quad \forall s \in S, \forall j \in J, \forall b \in B, \forall t \in T \tag{4.15}$$

$$\sum_{b \in B} R_{sbrt} \times \left(1 - \sum_{m \in M} p_{bm} \right) = \sum_{l \in L} N2_{srlt}, \quad \forall s \in S, \forall r \in R, \forall t \in T \tag{4.16}$$

$$Inv_{smrt} = Inv_{smr,t-1} + \sum_{b \in B} p_{bm} \times R_{sbrt} - N1_{smrt}, \quad \forall s \in S, \forall m \in M, \forall r \in R, \forall t \in T \tag{4.17}$$

$$R_{sbrt} = \sum_{j \in J} x2_{sjbrt}, \quad \forall s \in S, \forall b \in B, \forall r \in R, \forall t \in T \tag{4.18}$$

$$\sum_{q \in Q} ys_{jqt} \leq 1, \quad \forall j \in J, \forall t \in T \tag{4.19}$$

$$\sum_{i \in I} x1_{sijt} \leq \sum_{q \in Q} CAP\_s_q \times ys_{jqt} + \sum_{c \in C} c_c \times us_{jct'}, \quad \forall s \in S, \forall j \in J, t' \leq t \tag{4.20}$$

$$\sum_{c \in C} us_{jct} \leq 1, \quad \forall j \in J, \forall t \in T \tag{4.21}$$

$$\sum_{c \in C} \sum_{t \in T} us_{jct} \leq 3, \quad \forall j \in J \tag{4.22}$$

$$\sum_{b \in B} R_{sbrt} \leq CAP\_r_r \times yr_{rt}, \quad \forall s \in S, \forall r \in R, \forall t \in T \tag{4.23}$$

$$ys_{jqt} \leq ys_{jq,t+1}, \quad \forall j \in J, \forall q \in Q, t < T \tag{4.24}$$

$$yr_{rt} \leq yr_{r,t+1}, \quad \forall r \in R, t < T \tag{4.25}$$

$$yt_{krt} \leq yt_{kr,t+1}, \quad \forall k \in K, \forall r \in R, t < T \tag{4.26}$$

$$yl_{rt} \leq yl_{r,t+1}, \quad 1 \leq t < T \tag{4.27}$$

$$\sum_{j \in J} \sum_{b \in B} x3_{sjblt} + \sum_{r \in R} N2_{srlt} \leq y_{lt} \times M, \quad \forall s \in S, \forall l \in L, \forall t \in T \tag{4.28}$$

$$\sum_{j \in J} \sum_{b \in B} \sum_{t \in T} x3_{sjblt} + \sum_{r \in R} \sum_{t \in T} N2_{srlt} \leq CAP\_l_l, \quad \forall s \in S, \forall l \in L_N \tag{4.29}$$

$$\sum_{j \in J} \sum_{b \in B} \sum_{t \in T} x3_{sjblt} + \sum_{r \in R} \sum_{t \in T} N2_{srlt} \leq parExistCap\_L_l, \quad \forall s \in S, \forall l \in L_E \tag{4.30}$$

$$ys_{jqt} = 1, \quad \forall j \in J_E, q = 1, t = 1 \tag{4.31}$$

$$yl_{lt} = 1, \quad \forall l \in L_E, t = 1 \tag{4.32}$$

$$ro_{r,t-1} = yr_{rt} - yr_{r,t-1}, \quad \forall r \in R, \forall t \in T \tag{4.33}$$

$$us_{jct} \leq \sum_{q \in Q} ys_{jqt}, \quad \forall j \in J, \forall c \in C, \forall t \in T \tag{4.34}$$

$$yt_{krt} \leq yr_{rt}, \quad k \in K, r \in R, t \in T \tag{4.35}$$

$$R_{sbrt} \leq b_{brt} \times M, \quad \forall s \in S, \forall b \in B, \forall r \in R, \forall t \in T \tag{4.36}$$

$$b_{brt} \leq \sum_{k|tb_{kb}=1} yt_{krt}, \quad \forall b \in B, \forall r \in R, \forall t \in T \tag{4.37}$$

$$TS_{sjqt} \leq ys_{jqt} \times M, \quad \forall s \in S, \forall j \in J, \forall q \in Q, \forall t \in T \tag{4.38}$$

$$TS_{sjqt} \geq \sum_{i \in I} x1_{sijt} - (1 - ys_{jqt}) \times M, \quad \forall s \in S, \forall j \in J, \forall q \in Q, \forall t \in T \tag{4.39}$$

$$TS_{sjqt} \leq \sum_{i \in I} x1_{sijt} + (1 - ys_{jqt}) \times M, \quad \forall s \in S, \forall j \in J, \forall q \in Q, \forall t \in T \tag{4.40}$$

Non-negativity and integer constraints

$$x1_{ijt}, x2_{jbrt}, x3_{jblt}, R_{brt}, Inv\_m_{mrt}, Inv\_b_{brt}, N1_{mrt}, N2_{rlt}, z1_{jbt} \geq 0 \tag{4.41}$$

$$ys_{jqt}, yr_{rt}, ro_{rt}, yl_{lt}, yt_{krt}, us_{jct}, b_{brt} \in \{0,1\} \tag{4.42}$$

4.3 Computational Results and Discussion

Firstly, we solved scenarios individually and observed the results. Then, the scenario-based model is built, which can provide the decision makers with an adequate framework to investigate different patterns of waste battery return. We assumed that the base scenario occurs with probability of 0,40 and the other scenarios with probability of 0,20.

The model statistics of the deterministic equivalent model are 781602 non-zero elements, 17013 single equations, 53961 single variables, and 876 discrete variables. The objective function value is 81728.

Figure 4.1 shows the optimal network configuration for the 3 scenarios, respectively. As it is seen in Figure 4.1, waste battery collection pattern changes optimal network configuration. However, in all optimal network configurations, recycling facility is constructed at the same location. In Scenario 1, we assumed that the waste battery collection amounts are proportional to the population. In eastern, and southeastern regions of Anatolia, there are populated provinces that currently do not collect considerable amounts of waste battery. Hence, we observe constructed facilities at these regions in the optimal network configuration of Scenario 1. In Scenario 2, the effect of population is lesser compared to Scenario 1 and accordingly network slightly changes.

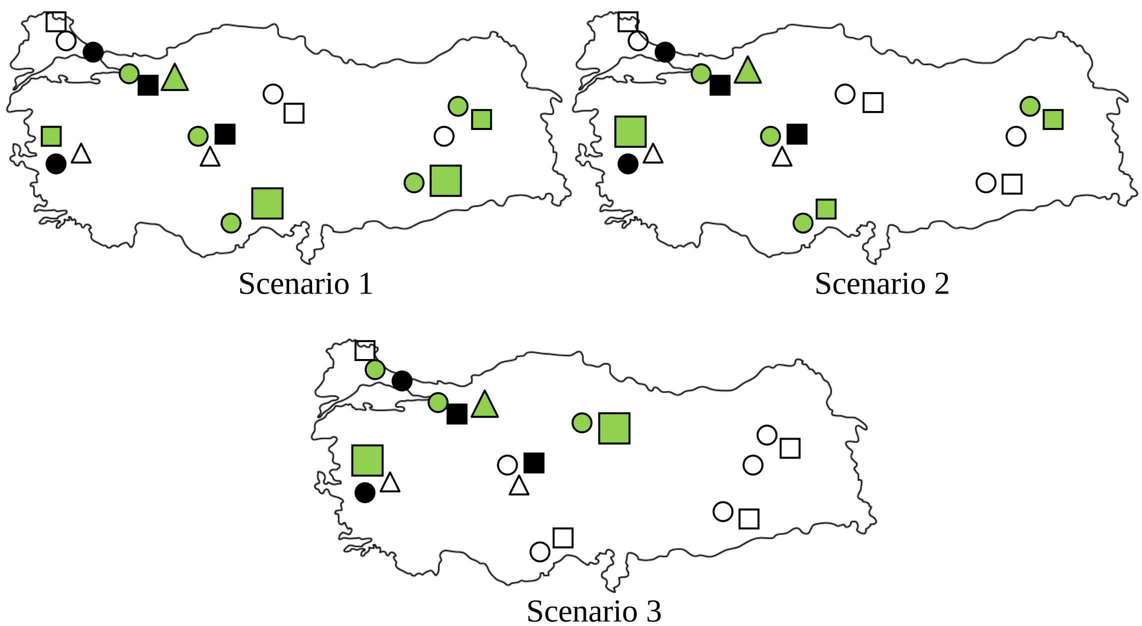


Figure 4.1: Optimal network configuration for each scenario

In Figure 4.2, the optimal network configuration for the deterministic equivalent model is illustrated which is a combination of all scenarios.

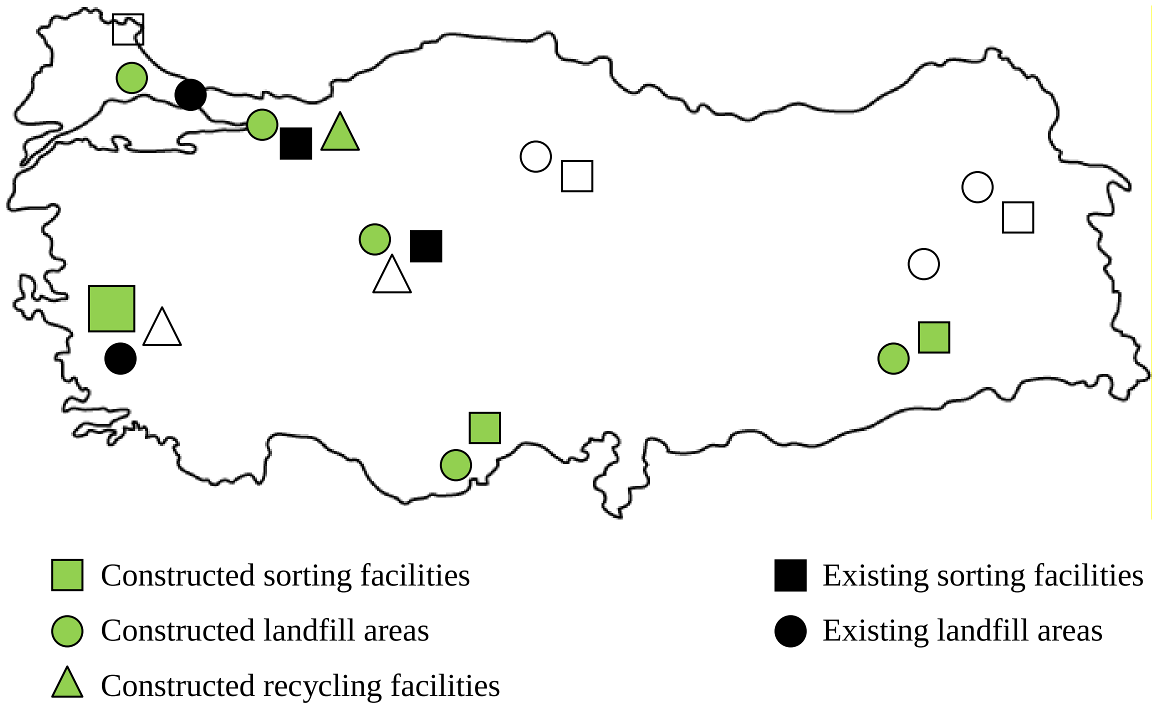


Figure 4.2: Optimal network configuration for the deterministic equivalent model

Expected Value of Perfect Information (EVPI)

The expected value of perfect information is the difference between expected outcome with the perfect information and the expected outcome without perfect information. The expected value with perfect information is the expected return, in the long run, if we have the perfect information before a decision has to be made. The perfect information solution chooses optimal first stage decisions for each realization of ε. The expected value of this solution is called as the 'wait-and-see' solution (WS) in literature. To calculate the expected value with perfect information (WS), we choose the best alternative for each state of nature and multiply its payoff with the probability of occurrence of that state of nature.

Let BO_s be the best outcome of each scenario *s* and P_s be the probability of scenario *s*.

$$WS = \sum_{s \in S} P_s \times BO_s \tag{4.36}$$

The outcome of the deterministic equivalent of the stochastic program gives the expected value without perfect information (DE). Hence, the expected value of perfect information (EVPI) is calculated using the following equation:

$$EVPI = WS - DE \tag{4.37}$$

	Probabilities	Optimal objective function value
Base Case	0,4	1249506
Scenario 1	0,2	-2144189
Scenario 2	0,2	199009
Scenario 3	0,2	1024503
Deterministic equivalent of the stochastic program		81728

Table 4.2: Optimal objective function values

Using Table 4.2 we calculated the EVPI.

$$WS = (0{,}4 \times 1249506) + (0{,}2 \times (-2144189)) + (0{,}2 \times 199009)$$
$$+ (0{,}2 \times 1024503) = 315667$$

$$DE = 81728$$

$$EVPI = 233939$$

4.4 Sensitivity Analysis

In order to determine the impacts of the uncertain parameters, a sensitivity analysis is performed. Tests are conducted for four parameters of the model; probabilities of the scenarios, return amounts of waste batteries and sale prices of recycled materials.

4.4.1 Probabilities of the scenarios

Assigning probabilities to scenarios incorporates some subjectivity. In order to analyze the impact of the probability of each scenario, the deterministic equivalent model is solved for different probability values which is depicted in Table 4.3.

	Base Case	Scenario 1	Scenario 2	Scenario 3
Run 1	0,40	0,20	0,20	0,20
Run 2	0,55	0,15	0,15	0,15
Run 3	0,36	0,22	0,22	0,22
Run 4	0,50	0,30	0,10	0,10
Run 5	0,50	0,10	0,20	0,20
Run 6	0,25	0,25	0,25	0,25

Table 4.3: Probabilities for each run

Figure 4.3 gives the optimal objective values for deterministic equivalent model, the expected value with perfect information (WS), and the EVPI (Expected Value of Perfect Information) for each run. As it is seen, while there is considerable differences in the optimal values, the EVPI is always within a specific range.

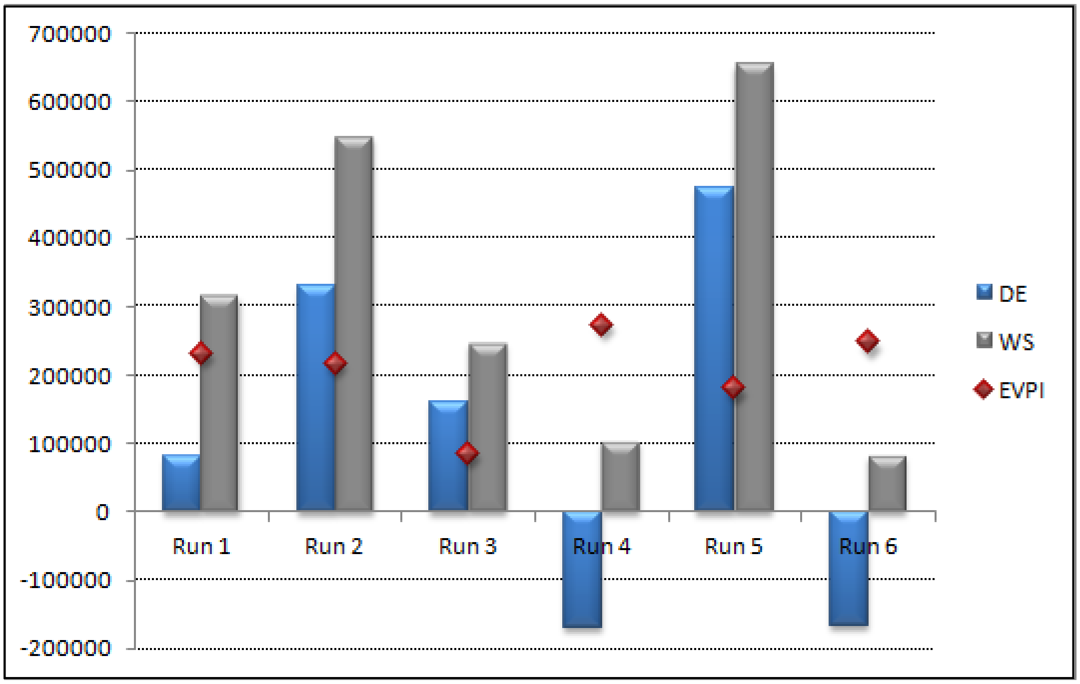


Figure 4.3: EVPI for each run

The optimal network configuration obtained by solving each model is almost same. The difference occurred just in the 4th and 5th runs. In the 4th run, the landfill area in Kırklareli is not used. In the 5^{th} run, instead of the landfill areas and sorting facilities which are located at Diyarbakır in other optimal network configurations, the facilities are located at Erzurum. These results show that the deterministic equivalent model is robust since no significant changes are observed in the optimal reverse network configuration.

4.4.2 Return amounts of waste batteries

The amount of returned products is stated as the main source of uncertainty in the reverse systems. In order to analyse the impact of the returned amounts, we generate a random parameter which is uniformly distributed between 0,9 and 1,1. The base case model is solved for 10 instances where the amount of waste battery collected in each collection point is the multiplication of the newly generated parameter with the values used in the base case.

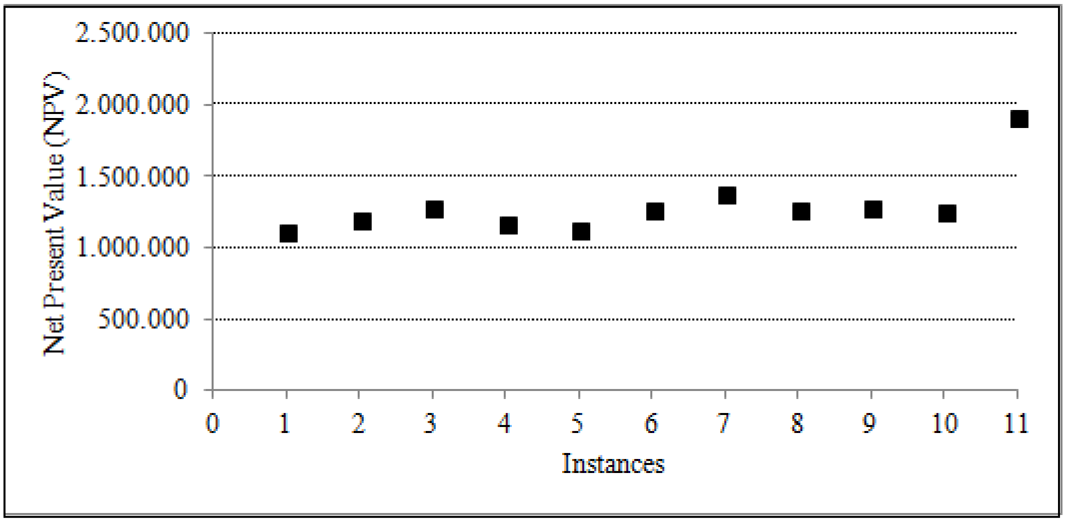


Figure 4.4: NPVs with varying waste battery collection amounts (10 instances) including an extreme case

As shown in the Figure 4.4, the amounts of returned waste batteries change the optimal NPVs. However, the optimal network configuration remains same as the base case in all instances. Also, an additional landfill area is used in this instance. All other solutions constructed facilities in same locations. The difference between the minimum and maximum NPV among 10 instances is 24% and the maximum NPV is 10,7% higher than the NPV of the base case. The extreme difference between recycling shares of instances and the base case is 0,4%.

The 11th instance shows an extreme case where waste battery collection increases 20%. The optimal network configuration does not change even in this situation. However, as it is seen, the net present value increased approximately 50% with an increase of 20% in the collection amounts. Thus, we conclude that a deviation of 10% from the forecasted collection amounts does not affect significantly neither the optimal configuration nor net present value, while an increase in waste battery collection can contribute net present value.

4.4.3 Sale Prices of Recycled Materials

In the base case and in all scenarios we used the forecasted data for the sale prices of recycled materials where the data published by U.S. Geographical Survey (USGS) is used. However as the price of scrap metals have a highly fluctuating structure; it is critical to assess the impact of variations in metal prices. In our model formulation, we consider holding recycled material inventory due to the practically fluctuating second market prices. With this sensitivity analysis we will also be able to observe the effect of fluctuating secondary market prices on inventory levels. Again, a random parameter is used which is uniformly distributed between 0,9 and 1,1. This parameter is assumed to be the revenue efficiency and we multiply each forecasted data with this parameter. 20 instances are solved and Figure 4.5 shows the data we used for the sale price of recycled Zinc in the first 5 instances. In Figure 4.6, the optimal values of 10 instances are seen. The average NPV of 10 instances is 2404464 which is 92% higher than the NPV obtained in the base case. This means that with low inventory holding cost and exact information about the sale prices of materials, high profits can be obtained. Furthermore, we observed that the variations in the sale prices of recycled materials increase recycling share in some instances. In three instances, the network changes slightly due to the increased recycling share. For these instances only, the sorting area in Mersin is not constructed and a landfill area is opened in Kırklareli instead of Mersin. For all other instances, the optimal network configuration is same as the solution of base case.

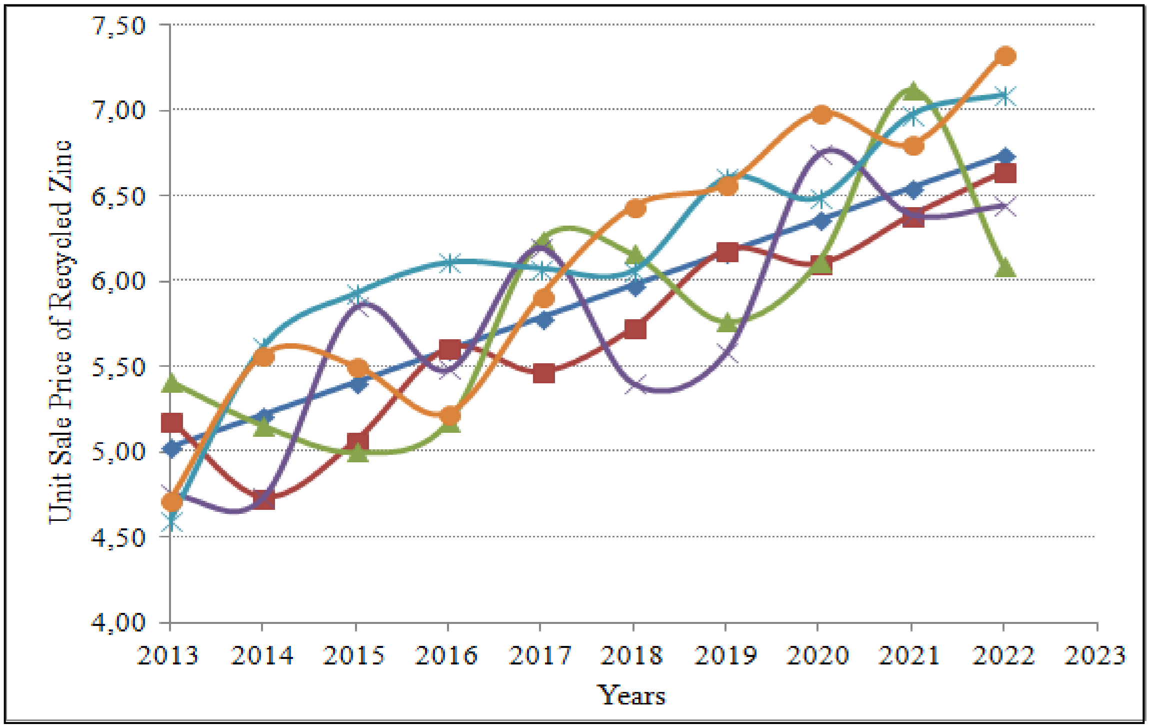


Figure 4.5: Data for sensitivity analusis of unit sale price of recycled materials (first 5 instances for recycled Zinc)

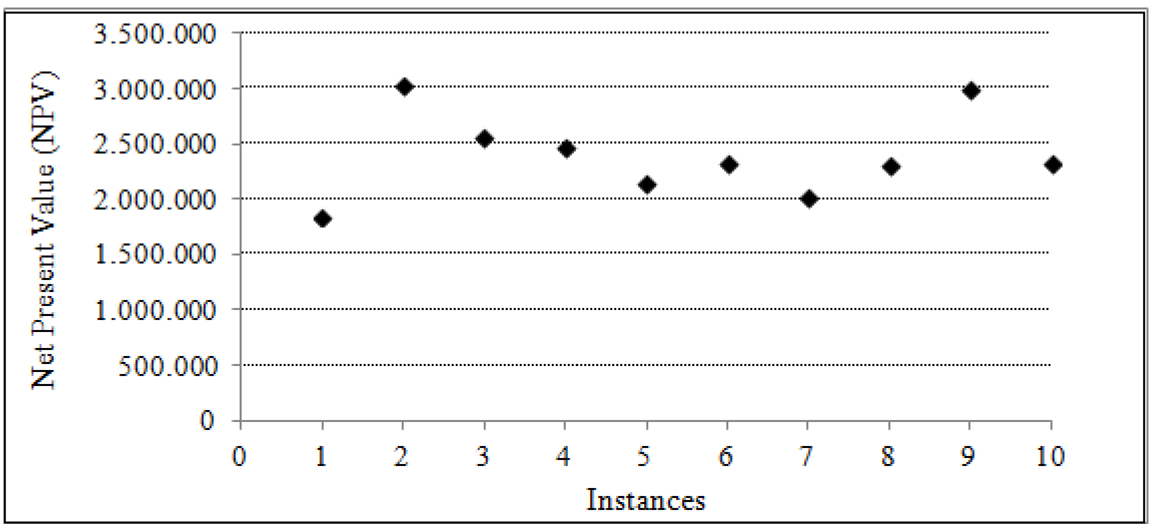


Figure 4.6: NPVs with varying sale prices of recycled materials (10 instances)

Chapter 5

CONCLUSIONS AND FUTURE RESEARCH

5.1 Conclusions

In this thesis, a reverse logistics network design model for waste batteries has been formulated and implemented to the Turkey case. As reverse processes are characterized by a high level of uncertainty, there is a necessity to consider uncertain factors. The deterministic model is extended by stochastic programming (scenario-based) to examine the effects of uncertain return of waste batteries on the network configuration. The optimization models are designed to answer questions about planning the location and timing of facility constructions, capacity expansions and network flows.

The specific goals and outputs that are accomplished within the scope of this research are as follows:

- A deterministic MILP model is developed and implemented.
- The data used in the model is described in detail and forecasts are done for some parameters.
- All-units discounts are performed for landfill operations as a second case and the effects of using all-units discounts are determined.
- The deterministic model is extended in order to capture the effects of uncertainty in the waste battery collections.

- Stochastic programming model is introduced with the aim of analyzing the impact of uncertainty and the deterministic equivalent is formulated via scenarios.
- Both models are implemented to Turkey case and the comparison of results is presented.
- Sensitivity analyses are conducted to assess the impacts of changes in critical parameters and to identify which parameters significantly influence the reverse logistics network design.

The objective functions of the models are profit-oriented which aims to maximize the total net present value gained through the system over a planning horizon of 10 years. The sorting cost is linearized by using exact linearization techniques in order to ensure the linearity of the model and avoid the computational challenges of large convex non-linear models. To reflect the characteristics of a multi-period setting, we used several time-dependent parameters, such as forecasted waste battery collection amounts and price of recycled materials, increasing fixed and variable costs of facilities, and construction lead times for recycling facilities. The capacity expansion decisions, multiple capacity options, and two disposal options for waste batteries are considered. All computational work has been executed on a personal computer (32-bit operating system, 2.50 GHz CPU, and 4.00 GB). The deterministic models are solved in a run time of approximately 6,5 minutes, while the deterministic equivalent model that is presented in Chapter 4 is solved in 166 minutes which is approximately 2,7 hours.

As a summary, we showed that using all-units discounts provide incentive to landfill more which is undesirable in our setting. The significance of the returned amounts of waste batteries is proved via scenario analysis. The optimal network configuration varies depending on the collection amounts of collection points. The overall net present value is directly affected by sale prices of recycled materials, and the return amounts, while these parameters does not cause a significant change in the optimal network configuration. We give the optimal network configuration we obtained under uncertainty.

5.2 Recommendations for Future Research

This research can be expanded in several ways.

The developed model does not take into account waste battery collection activities and associated collection cost. As a future work, the model can be extended by including battery collection activities, cost and different collection options. Moreover, in the case of having available data on the amount of waste batteries in circulation, collection targets determined by the legislations can be added and associated penalty cost can be incurred. This approach can give insight into the effects of legislations on waste battery management.

Another direction can be the examination of the effects of uncertainty in the model by using different methods such as robust optimization and making comparison between the results obtained by different methods. Moreover, it can be useful to take into account other uncertain factors in the model in addition to the return of waste batteries.

The computation time for running the deterministic equivalent model is approximately 3 hours. The mathematical formulation can be strengthened by modifying some constraints which can affect the computation time positively.

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APPENDIX A

In this Appendix, we present the information about the content of waste batteries and the details of the initial setting for the case study. Figure 1 depicts the collection points on the map of Turkey.

Table 1 and Table 2 gives the material composition of different batteries and the recoverable materials for each battery type, respectively.

Battery Type	Mercury	Lead	Zinc	Manganese	Iron
Alkaline Manganese	0.0013	0.04-2	35	28	28
Zinc-carbon	0.0005	0.15-2	35	18	21
Portable NiCd			0.06	0.083	29-40
Portable NiMH				0.81-3	20-25
Portable Li-based				10-15	4.7-25

Table 1: Material composition of different batteries in % by weight

Non-recyclable batteries		Rechargeable batteries					
General purpose	Metals recoverable	NiCd	Metals recoverable	NiMH	Metals recoverable	Li-ion	Metals recoverable
Zinc	20%	Cadmium	15%	Nickel	40%	Acier	22%
Manganese	20%	Nickel	25%	Steel	18%	Cobalt	17%
Iron	20%	Steel	35%				
Cupper	10%						
Total	70%	Total	75%	Total	58%	Total	39%

Table 2: Metals recoverable % weight per battery

Table 3 depicts all costs associated with the recycling activity and fixed and variable costs of landfill areas. The construction cost of landfill areas are given in Table 4. In Figure 1, the incentive regions of Turkey is illustrated which we used for determining the construction and fixed costs.

Cost associated with sorting activities are shown in Table 5 and Table 6. Finally, Figure 2 to 7, show the double exponential smoothing results we found for the recycled materials.

Description		**Parameter**	**Values**
Construction cost for recycling facilities		CCR_{r1}	5.10^{6}
Fixed cost for recycling facilities		FCR_{r1}	6.10^{4}
Cost of installing technology		FCT_{11}	5.10^{4}
		FCT_{21}	7.10^{4}
		FCT_{31}	1.10^{5}
Unit inventory holding cost		UCI_{1}	5.10^{-1}
Unit cost of landfill operations		UCL_{l1}	$2{,}05.10^{-1}$
Unit cost of recycling operations	Zincbased	UCR_{br1}	2,15
	Ni-based	UCR_{br1}	2,25
	Li-based	UCR_{br1}	2,50

Table 3: Costs occured at recycling facilities in the beginning of the planning horizon

Figure 1: The new incentive regions of Turkey

Landfill area	CCL_{l1}
ANKARA	116200
CORUM	83500
DIYARBAKIR	96300
ERZURUM	81400
KIRKLARELI	86300
KOCAELI	166200
MERSIN	97200
BINGOL	81600

Table 4: Landfill area construction cost for the initial year

Description		**Parameter**	**Value**
Capacity expansion cost			
	Lo	$FCCS_{j11}$	$2{,}5.10^4$
	Mi	$FCCS_{j21}$	$4.\ 10^4$
	Hi	$FCCS_{j31}$	$5.\ 10^4$
Unit cost of sorting			
	Lo	UCS_{j11}	0,66
	Mi	UCS_{j21}	0,53
	Hi	UCS_{j31}	0,32

Table 5: Costs associated with sorting operations for the initial year

Investment Region		CCS_{jq1}	FCS_{jq1}
1	Lo	240000	16000
	Mid	390000	26000
	Hi	465000	31000
2	Lo	225000	15000
	Mid	375000	25000
	Hi	450000	30000
3	Lo	210000	14000
	Mid	360000	24000
	Hi	435000	29000
4	Lo	195000	13000
	Mid	345000	23000
	Hi	420000	28000
5	Lo	180000	12000
	Mid	330000	22000
	Hi	405000	27000
6	Lo	165000	11000
	Mid	315000	21000
	Hi	390000	26000

Table 6: Construction and fixed costs for sorting facilities for the initial year.

	Capacity Levels for Sorting Facilities (CAP_s_q)	Capacity Expansion Levels for Sorting Facilities (c_c)
Lo	200000	50000
Mi	400000	80000
Hi	500000	125000

Table 7: The capacity options and capacity expansion levels for sorting facilities

Existing Sorting Facility	Capacity (Kg/Year)	Existing Landfill Area	Capacity (Kg)
ANKARA	200000	ISTANBUL	500000
KOCAELI	200000	IZMIR	250000

Table 8: Capacities of potential and existing landfill areas

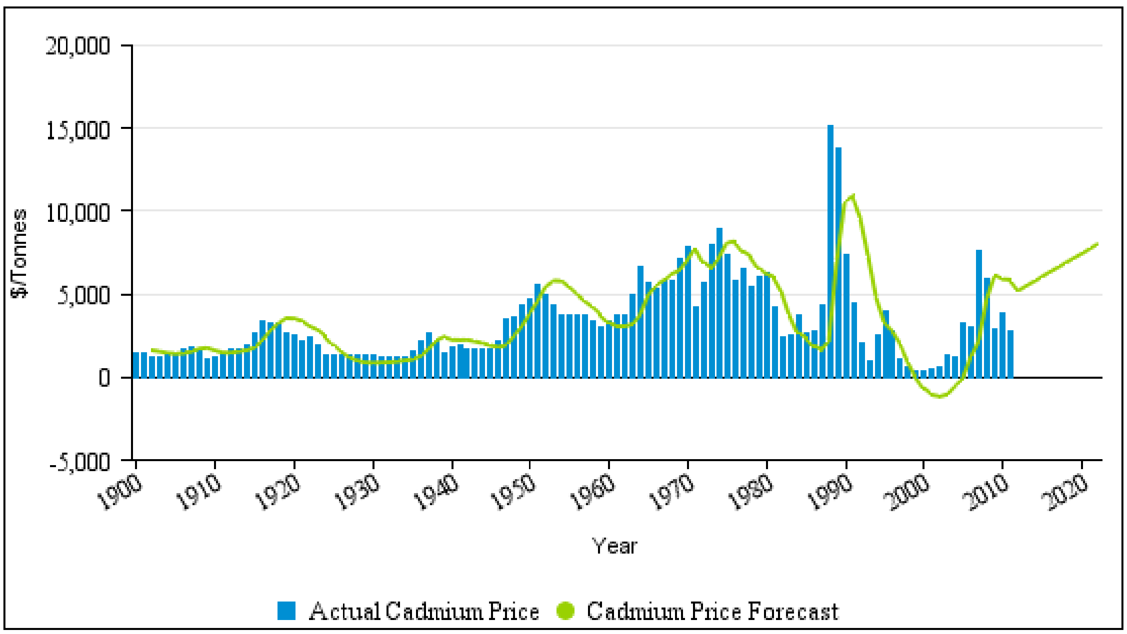

Figure 2: Actual and forecasted prices of Cadmium

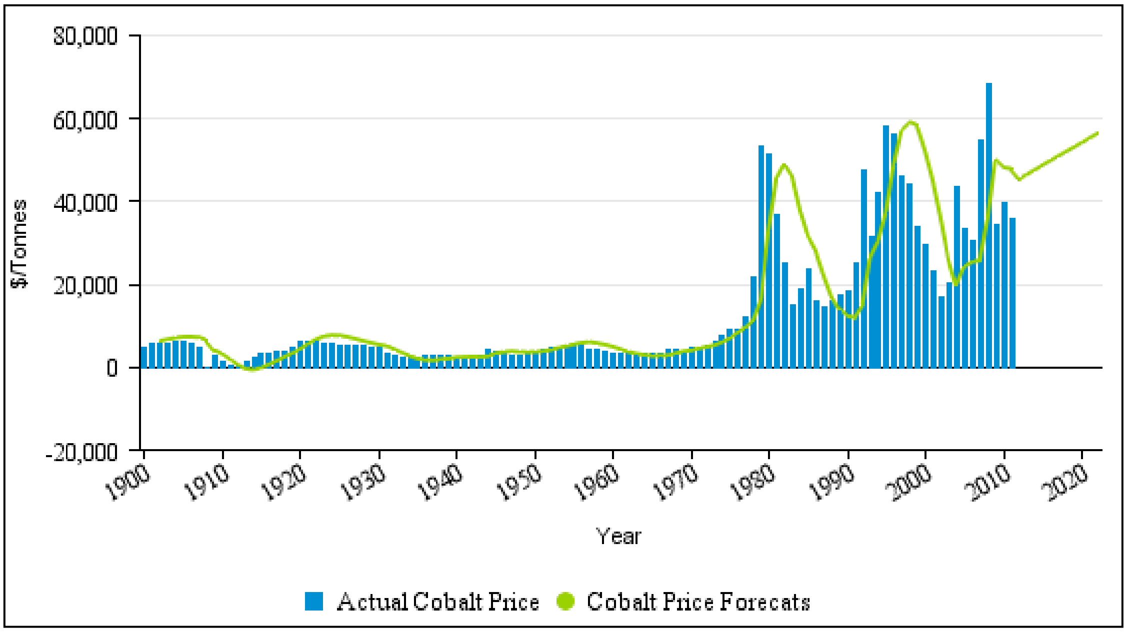

Figure 3: Actual and forecasted prices of Cobalt

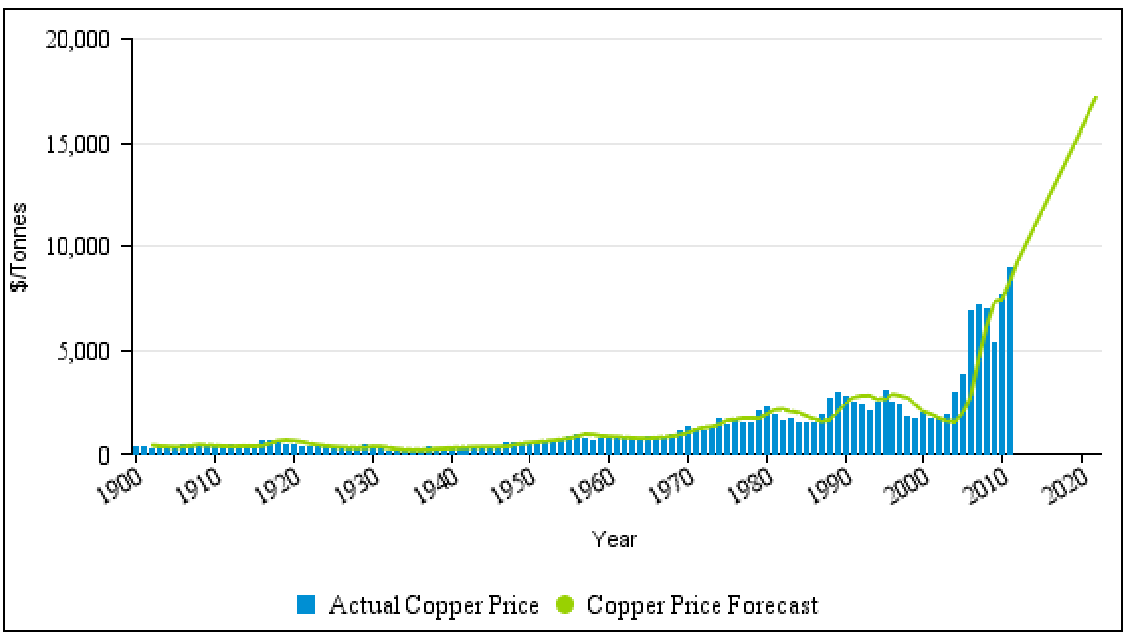

Figure 4: Actual and forecasted prices of Copper

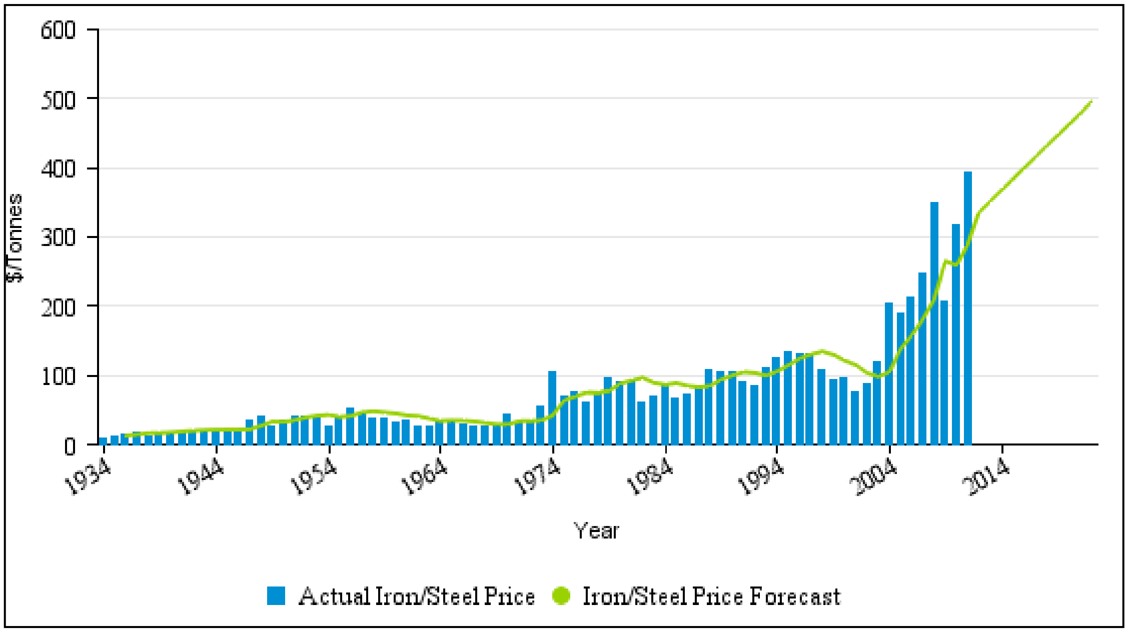

Figure 5: Actual and forecasted prices of Iron/Steel

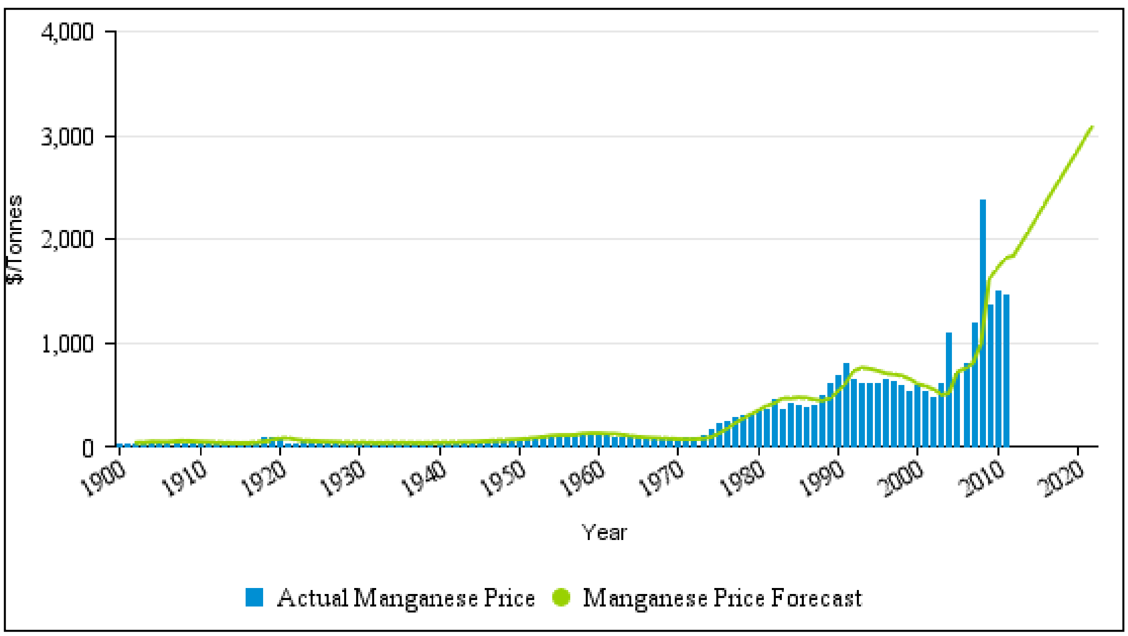

Figure 6: Actual and forecasted prices of Manganese

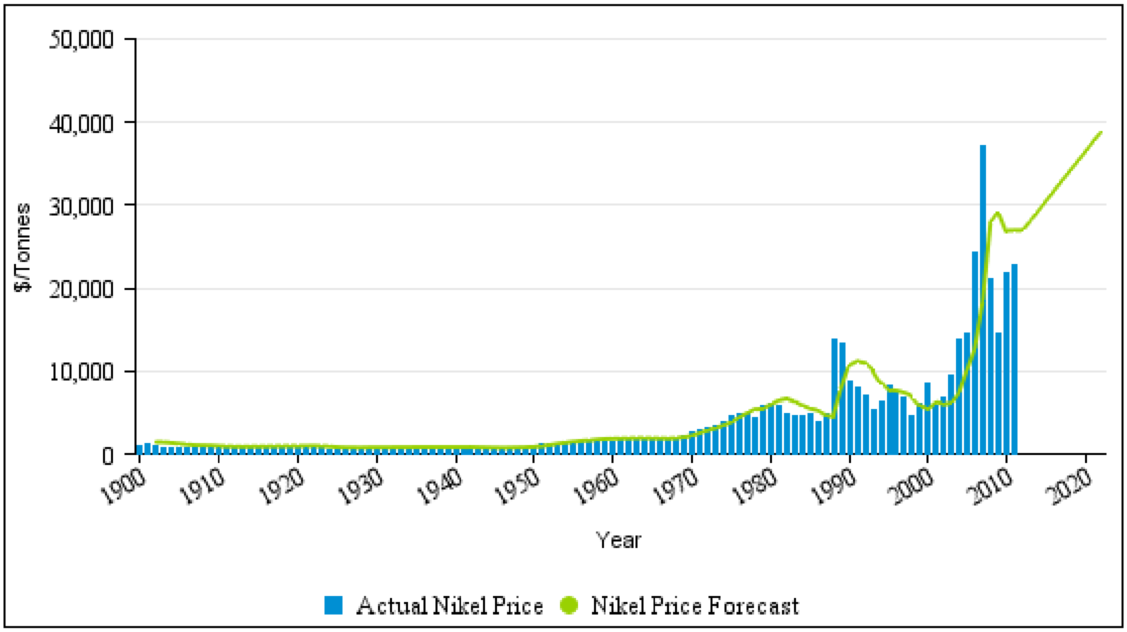

Figure 7: Actual and forecasted prices of Nickel

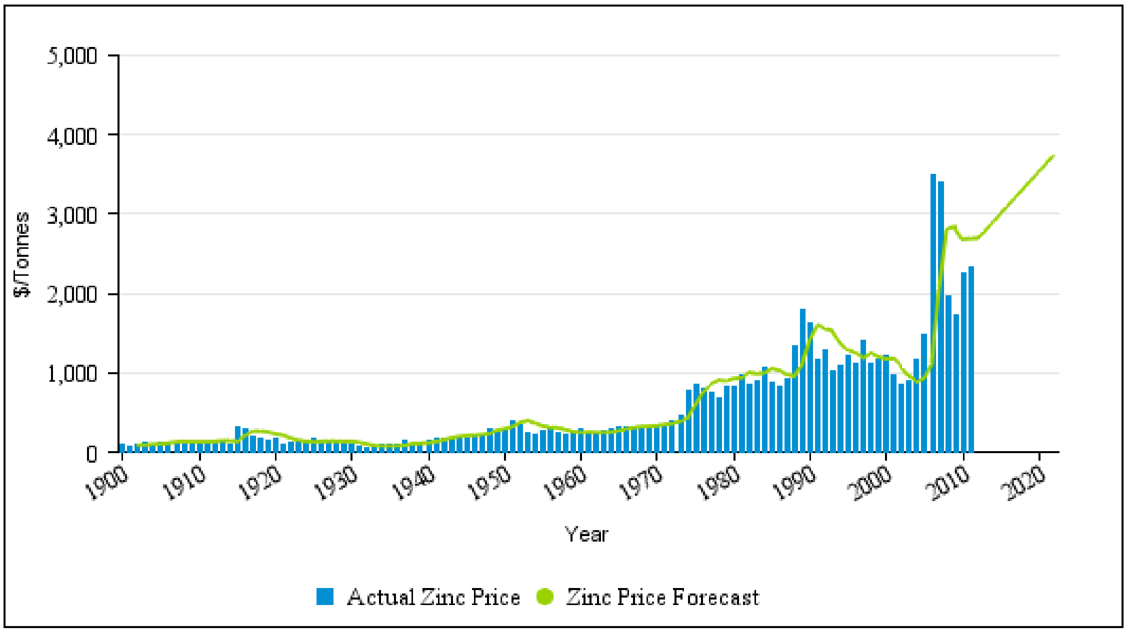

Figure 8: Actual and forecasted prices of Zinc

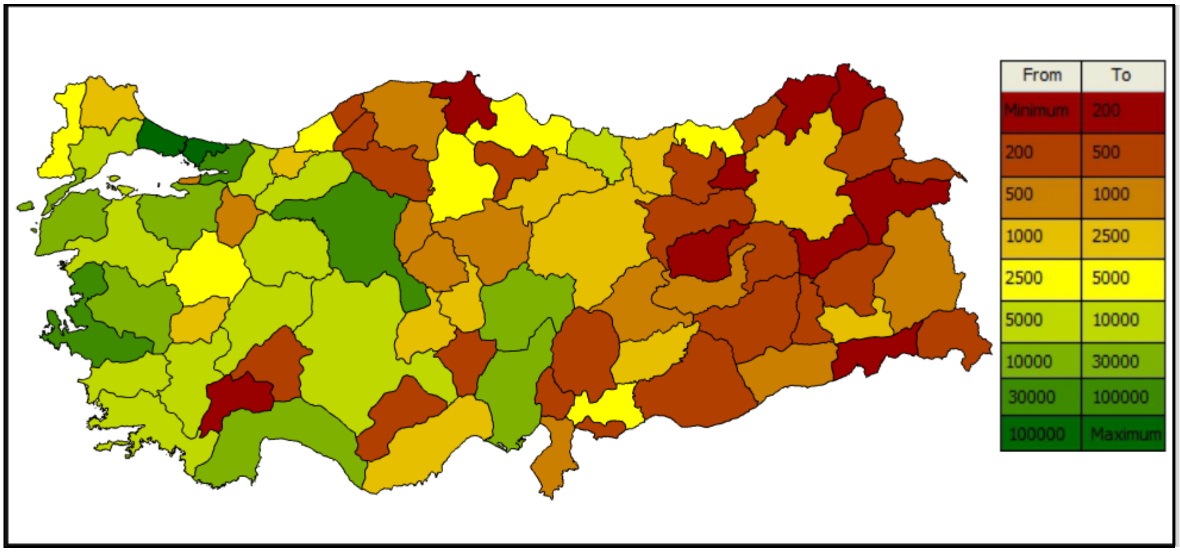

Figure 9: Illustration of collection for base case

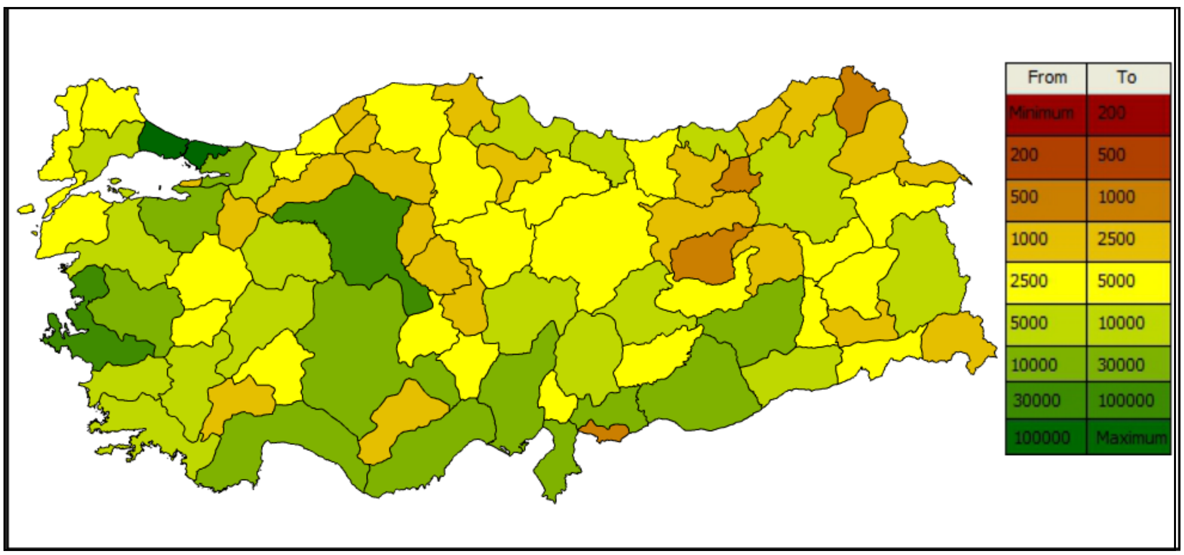

Figure 10: Illustration of collection for Scenario 1

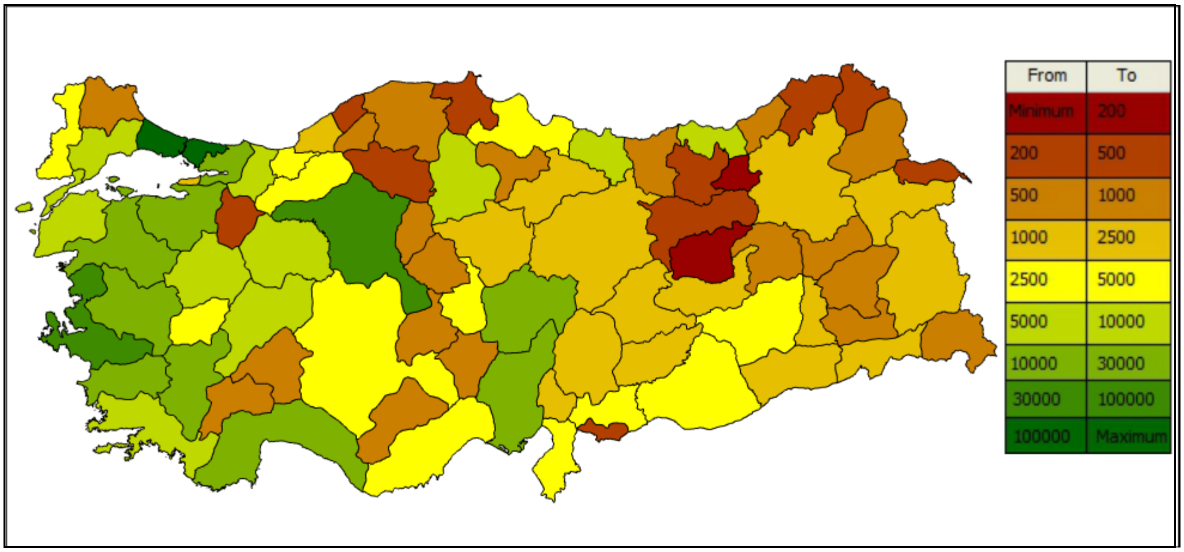

Figure 11: Illustration of collection for Scenario 2

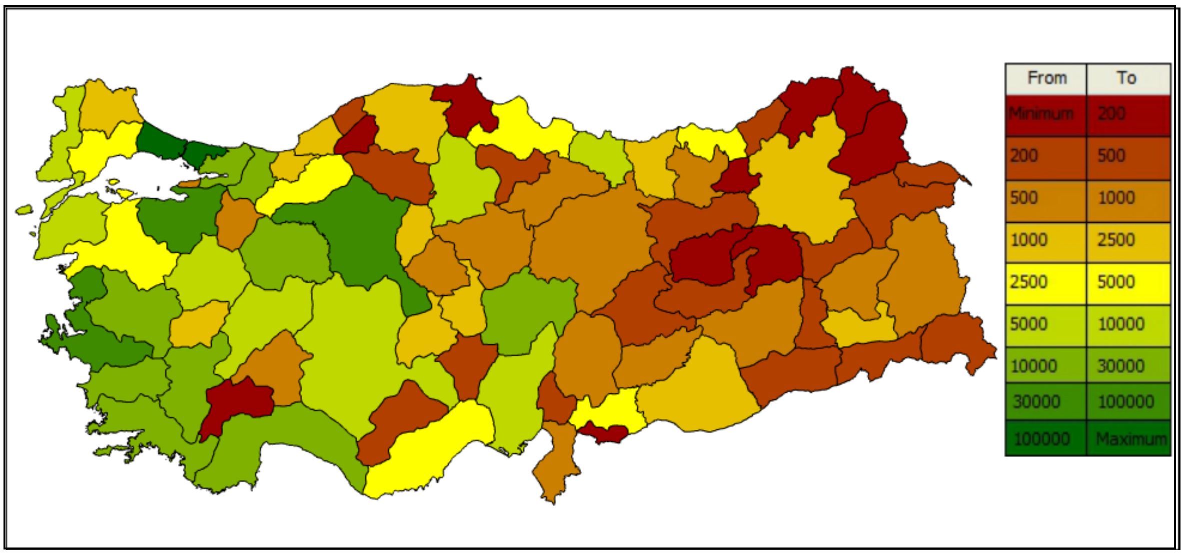

Figure 12: Illustration of collection for Scenario 3

VITA

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