ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL OF SCIENCE
ENGINEERING AND TECHNOLOGY

A MULTI-OBJECTIVE MATHEMATICAL MODEL FOR THE OPERATIONS PLANNING OF A REVERSE LOGISTICS FACILITY AND AN APPLICATION

M.Sc. THESIS

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Department of Industrial Engineering

Industrial Engineering Programme

AUGUST 2017

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ISTANBUL TEKNİK ÜNİVERSİTESİ ★ FEN BİLİMLERİ ENSTİTÜSÜ

TERSİNE LOJİSTİK TESİSİNİN OPERASYON PLANLAMASINA İLİŞKİN ÇOK AMAÇLI BİR MATEMATİKSEL MODEL VE BİR UYGULAMA

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To my beloved family,

FOREWORD

In this thesis, an increasingly important topic, Reverse Logistics, investigated and a mixed-integer linear programming model (MIP) proposed based on the perspective of driving forces. Legislations, environmental concerns and economic benefit are considered while constructing the model.

The proposed model has two objective functions, one of them aims to minimize the cost and the other one is maximize the total amount of properly disposed most hazardous materials amount. This multi-product, multi-period and multi-objective model implemented to an existing refrigerator recycling facility. Based on the recycled materials' sales price and fixed and variable costs, operations planning decisions proposed. Sensitivity analyses are conducted by changing the parameters.

I would like to thank my esteemed advisor Assoc. Prof. Şule Itır SATOĞLU for her contributions in the all stages of my thesis. I also thank my family and my dear friends for their continuous support.

July 2017

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(Industrial Engineer)

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ABBREVIATIONS

MIP : Mixed Integer Programming
GAMS : General Algebraic Modeling System
RL : Reverse Logistics
RLND : Reverse Logistics Network Design
RCCP : Rough Cut Capacity Planning
WEEE : Waste Electrical Electronic Equipment
EE : Electrical Electronic Equipment
DM : Decision Maker
R : Range

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SUMMARY

In today's world, the materials that are recycled or remanufactured, especially electronic waste, provide a solution for declining natural resources. Because of the rapid increase in consumption in the developing countries, searching for new naturel sources or reusing the existing resources is gaining importance and become one of the trend topics.

Reverse logistics activities are inevitable for companies that want to prevent environmental pollution due to harmful wastes and to obtain economic advantages by evaluating these wastes. Regulations that are implemented in many developed countries and soon to be implemented in Turkey, will also make reverse logistic activities compulsory.

Due to the ambiguous parameters involved, in the reverse logistics chain, which has a rather complex structure than a conventional supply chain, obtaining positive results is quite difficult. Reverse logistics, includes all operations related to the collection, assessment, recovery and disposal of these wastes in an appropriate way. Many studies have been carried out to optimize collection and transportation costs, which are considered the most important expense items in logistics.

In this thesis, refrigerators are examined in particular, composition and recyclability rates of them evaluated to calculate the financial gain and disposal costs of hazardous parts. While the dangerous refrigerants used in the refrigerators are banned all over the world, there are still refrigerators in the market that contain these and other dangerous gases and liquids. Authorized special firms provide firms suitable disposal of these hazardous materials generally for money. This is also burden for reverse logistics companies.

In this study, a multi-objective, multi-product and multi-period MILP mathematical model for a reverse logistics firm was proposed. Under various constraints, whether to collect products from the specified regions, determining the required source amounts and inventory decisions were discussed. In addition, Sensitivity analysis was conducted with various scrap prices to have better understanding.

TERSİNE LOJİSTİK TESİSİNİN OPERASYON PLANLAMASINA İLİŞKİN ÇOK AMAÇLI BİR MATEMATİKSEL MODEL VE BİR UYGULAMA

ÖZET

Dünyada, özellikle de gelişmiş ülkelerde, elektronik atıklar başta olmak üzere, geri dönüştürülerek yada tekrar kullanılarak değerlendirilen kaynaklar, azalan doğal kaynaklar için bir çözüm önerisi oluşturmaktadır.Özellikle gelişmekte olan ülkelerde de tüketimin hızla artması nedeniyle, yeni doğal kaynak arayışları veya kaynakların tekrar kullanılması en önemli gündemlerden biri haline gelmiştir.

Gerek zararlı atıklar sebebiyle artan çevre kirliliğini önlemek gerekse bu atıkları değerlendirerek ekonomik avantaj elde etmek isteyen firmalar için Tersine Lojistik faliyetleri kaçınılmaz olmuştur.Bir çok ülkede yürürlükte olan ,Türkiye'de de yakın zamanda yaptırımları uygulanmaya başlayacak olan yönergeler de tersine lojistik uyulamalarını zorunlu hale getirecektir.

Tersine lojistik de, bu atıkların toplanması, değerlendirilmesi, geri kazandırılması yada zararlı olanların uygun şekilde imha edilmesi ile ilgili operasyonların tümünü içerir. Tersine lojistikte en önemli gider kalemi olarak görülen toplama ve taşıma maliyetlerini optimize etmek için birçok çalışma yapılmıştır.İçerdiği belirsiz parametreler sebebiyle, klasik bir tedarik zincirine göre oldukça kompleks yapıya sahip olan tersine lojistik zincirinde, aynı anda hem ekonomik hem de çevresel açıdan avantaj elde edip, pozitif sonuçlar almak oldukça zordur.

Çalışmada özellikle buzdolabı geri dönüşümü incelendiği için, buzdolabını oluşturan parçalar ve geri dönüştürülebilme oranları üzerinden elde edilebilecek maddi kazanç incelenmiştir.Buzdolabında kullanılan soğutucu gazlar (refrigerant) tüm dünyada yasaklanmış olsa da, piyasada bu ve bunun gibi tehlikeli gazları bulunduran bozdolapları ve soğutucular hala bulunmaktadır.Bu zararlı gaz ve yağların imhası için yetkilendirilmiş firmalar aracılığıyla uygun imha koşulları sağlanmaktadır.

Bu çalışmada, bir tersine lojistik firması için çok amaçlı, çok ürünlü ve çok periyodlu bir matematiksel model oluşturulmuştur.Çeşitli kısıtlar altında bölgelerden ürün toplayıp toplamama kararları, gerekli kaynak miktarlarını belirleme ve envanter kararları ele alınmıştır.Ayrıca, firmalar için tersine lojistik faaliyetleri yapmanın uygun olduğunu anlamak adına hurda değerleri ile duyarlılık analizi yapılmıştır.

Tersine lojistik ağı, tüm üretim sistemleri ve ürün türleri için tasarlanabilir. Beyaz eşya, pil, bilgisayarlar da dahil olmak üzere kum, halı, ahşap ve elektrik elektronik ürünler tersine lojistik ağına dahil edilmiş ürünlerdir.Atık elektrik elekronik eşyalar, kullanım ömrü sona eren ve en az bir elektrik elektronik parça içeren elektronik cihazlardır. Elektronik cihazlar birden fazla nedenden dolayı atık olarak kabul edilebilir; ürün kırılmış olabilir, teknolojik nedenlerle atılması gerekebilir veya modası geçmiş gibi görünebilir.

Tedarik zinciri kurulumu mümkün olsa da, iade edilen ürünün bileşimi ve miktarındaki belirsizlik nedeniyle, tedarik zinciri yönetimi bilgisini atık ürün toplama ve değerlendirme süreçlerine entegre ederken engeller bulunmaktadır. Buradaki

belirsizliklerin hepsi birden göz önüne alınamasa da, belirsizlikler modele dahil edilmelidir.Karmaşık yapısı nedeniyle, verimli bir RL ağ tasarımı oluşturmak zorludur. Hedeflenen yeniden üretim ve geri dönüştürme oranlarına ulaşmak için sorumluluklar firmalar, halk ve devlet arasında paylaşılmalıdır. Tedarik zincirinde hem tüketicinin hem de şirketin çevresel ve sosyal etkileri üzerinde etkisi vardır.

RL karmaşık yapısı nedeniyle firmalar tarafından bir maliyet unsuru olarak görülmektedir. RL faaliyeti maliyetini azaltmak için devlet teşvik verebilir.Bununla birlikte artan geri dönüştürülen ürün miktarı ile birlikte firmaların maliyeti de azalacaktır.

Makalelerin çoğu tersine lojistik ağ tasarımı hakkında yazılmıştır. Tersine lojistik ağı, kullanılan ürünlerden elde edilen değeri arttırmak için süreç akışını optimize etmek üzere tasarlanmasıdır. Bu nedenle atık yönetiminden ayrılmıştır. Bu ürünlerin nerede ve nasıl toplandığı, nasıl incelendiği, hurda ürünler için bertarafının nasıl yapıldığı, işleme tabi tutulan ürünlere nerede ve nasıl uygulanacağı ve geri kazanılan ürünlerin nasıl dağıtılacağı konularını içerir. Ancak, geri dönüştürülen ürünlere olan talebin tahmin edilmesi, ne kadar ürün toplanacağı ve toplanan ürünlerin en uygun şekilde nasıl taşınması gerektiği, RL tesisinin üretim planlaması gibi henüz yeterince çalışılmayan konuların çalışılması da tersine lojistiğin daha iyi anlaşılmasına yardımcı olabilir ve ayrıca uygun geri dönüştürme yöntemleri geliştirilebilmesi için katkı sağlayabilir.

Türkiye, 79 milyondan fazla nüfusa sahip gelişmekte olan bir ülkedir. Teknolojideki bu gelişmelere ayak uydurmak isteyen insanlar daha fazlasını satın almak istemektedirler. Ülkedeki kişi başı güncel e-atık miktarı 6.6 kilogramdır. Günümüzde bazı belediyeler kağıt ve elektronik atık toplanması için özel bir gün ayırmaktadırlar ancak bunlar çok az sayıdadır.

Ülkemizde, Türkiye'nin AB üyeliği sürecinde WEEE yasaları çıkmaya başlamıştır. Mayıs 2012'de, Çevre ve Şehircilik Bakanlığı, Atık Elektrik ve Elektronik Cihazların Kontrolü Yönetmeliği'ni (AEEE) yayınladı. Bununla birlikte, altyapı, bilgi ve yasal yaptırımların eksikliği nedeniyle uyulamada çok başarı elde edilemedi.AEEE firmalara ürün kategorisine göre belirli geri dönüşüm hedefleri koymaktadır.Türkiye'de yasalar ve teşviklerin eksikliği, bu hedeflerin gerçekleştirilmesi için engel oluşturmaktaydı ve firmalar yüksek maliyet ve sistem gereksinimleri nedeniyle RL faaliyetlerini uygulamaktan çekinmekteydirler. Bununla birlikte, yeni yaptırımlar nedeniyle, büyük ölçekli işletmelerin çoğu kendi RL ağını oluşturmuştur veya oluşturmaya başlamıştır. Şimdi, 2017'de AEEE tekrar incelenmeye çalışılıyor ve kapsamının katı cezalarla genişletilmesi planlanıyor. Bu da bu alanda sürekliliği sağlayacaktır.

Bu çalışmada varolan ve buzdolabı geri dönüşümü yapan bir tersine lojistik tesisi incelenmiştir. Modelde iki amaç hedeflenmiştir. Birinci amaç fonksiyonunda, işgücü maliyeti, verilen bölgede kullanılan atık ürün toplama sisteminin kurulum maliyeti, lojistik maliyeti (her tur için bir kamyonun nakliye ve sabit masrafı), makine maliyeti, toplam elde tutma maliyeti, tesisin yıllık sabit maliyeti ve tehlikeli atık bertaraf maliyeti, maliyet parametreleridir. Hurda olarak satılan geri dönüştürülen malzemelerden elde edilen gelir, toplam maliyeti bulmak için maliyet kalemlerinin toplamından çıkarılır.Diğer amaç fonksiyonunda ise, düzgün şekilde bertaraf edilen zararlı materyallerin miktarı maksimize edilmiştir. Malzemelerin hepsi tehlikeli değildir, yalnızca en tehlikeli olan maddeler dikkate alınmıştır.

Parametreler çeşitli kaynaklardan toplanmıştır. Çoğu parametre değeri Eskişehir'de bir buzdolabı geri dönüşüm tesisinden, diğer değerler ise daha önceki kaynaklardan ve çevrimiçi kaynaklardan toplanmıştır. Tam değerlerini bulamadığımız parametreler için, mevcut verilere göre yaklaşık değerler kullanılmıştır. Devlet 10 farklı kategori için geri dönüştürme hedefleri belirlemiştir. Bu hedefler, bir önceki yıla ait satış rakamlarıyla çarpılarak o yıla ait hedef geri dönüştürme miktarları belirlenmiştir.

Modelde ev tipi ve tezgâh altı olarak da bilinen bar tipi buzdolabı olmak üzere iki tip buzdolabı toplandığı ve geri dönüştürüldüğü kabul edilmiştir. Malzeme içeriği buzdolabı tipi ve hacmine göre farklılık gösterir. Geri dönen ürün miktarı, basit gecikme(Simple delay method) metodu ile yapılmıştır. Geçmiş yıllara dönük satış ve üretim verileri sayesinde ileriki yıllar için satış ve üretim tahminleri yapılmıştır. Firmalar sadece yarıyıllık satışlarını paylaştıkları için bu tahmin 6 aylık satış rakamları göz önüne alınarak yapılmıştır.

Geliştirilen modelin çözümü için GAMS kullanılmıştır.2014-2018 yılları arasında hem ağırlık olarak hem de adet olarak hedef verilmesi durumlarındaki amaç fonksiyon değerleri bulunmuş ve karşılaştırılmıştır. Son olarak hangi parametrelerin kritik olduğunu saptamak ve kritik parametrelerdeki değişimin amaç fonksiyonuna etkisini ölçmek için duyarlılık analizi yapılmıştır.

Kapasite artışı, hedefler arttığında ilave bir işleme tesisi gerektirebilir. Ülkenin diğer bölgelerinde ikinci tesisin kurulması, taşımacılık maliyetlerinin düşürülmesi ve o bölgede sanayileşme ve istihdama katkıda bulunmak açısından çok faydalı olacaktır.

Hedefler büyüdükçe, toplanması gereken ürünlerin sayısı artacaktır. Hedeflere ulaşmak için, halkın yeterli bilince sahip olup olmadığını araştırmak ve yeterli miktarda ürün toplamak için teşvik verilmesi gerekiyor olabilir.

Hurda değerleri, kurmakta olduğumuz RL modeli için hassas parametrelerdir. Bu nedenle, maliyet hesaplamalarını doğru yapmak için önümüzdeki yıllarda parametre tahminleri doğru yapılmalıdır.

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1. INTRODUCTION

The depletion of the natural sources as a consequence of rapid industrialization, motivate both human being and manufacturers to find ways to extend the usage time of these sources. Nature friendly processes are being developed and concrete plans are being made to ensure the sustainability. Especially with the increase in the consumption in the third world countries, tendency to these issues increased.

While the nature and humans are struggling with these issues, very tough competition has seen among firms and each firm tries to forge ahead somehow to survive. In logistics, which is one of the major units of cost, advanced solutions are proposed including environmentally conscious steps. Green logistics, sustainability and reverse logistics are the terms that are emerged with these concerns. With well-designed and applicable strategies, both economically and environmentally advantageous outcomes can be obtained at the same time.

Green logistics first mentioned in 80's however it is started to implement in real world problems in 2000's. United States of America, Europe and Canada are the pioneers and they are followed by the Japan, China, Korea and Taiwan while developing countries like Turkey are just in the beginning phase. Green Logistics consider only environmental conditions, Reverse Logistic however look both economic and environmental perspectives, and try to balance the trade-off between them. According to Fleischmann (2001) "reverse logistics is the process of planning, implementing and controlling the efficient, effective inbound flow and storage of secondary goods and related information opposite to the traditional supply chain directions for the purpose of recovering value and proper disposal''.

Reverse logistics is generally considered as reverse of forward logistics and they are similar, however reverse logistics is much more complex since it includes complicated returned product collection and recovery processes with uncertain parameters. However it's hard to implement structure, companies especially that are large-scale, prefer to construct RL supply chain because of the driven forces of RL that are economic benefit, forcing legislations and environmental concerns.

Because of RL' complex structure, designing an efficient network is challenging. Reverse logistics consist of all activities including management, process and disposal of the hazardous and non-hazardous waste and packaging and usage of the product. In other words, it is all of the operations related with making the product reusable by some processes or dispose it properly. Responsibilities should have shared among the firms, civilians and government to achieve the targeted remanufacturing rates. In the supply chain, both consumer and the company have effect on environmental and social influences. Therefore, for example in Japan RL activities are one the most attractive social responsibility works (Sudarto et al, 2016). According to United Nations University's Waste Electrical and Electronic Equipment (WEEE) report, technical costs of four main processes are showed in Figure 1.1 for five types of WEEE (HLHA: Large Household Appliances, C&F: Cooling and freezing Small Household Appliances, S&A: Small Household Appliances). As can be seen, the cost varies from product to product. In some products the cost is mostly due to the processes applied to the products, while in some cases the transportation is the most expensive factor.

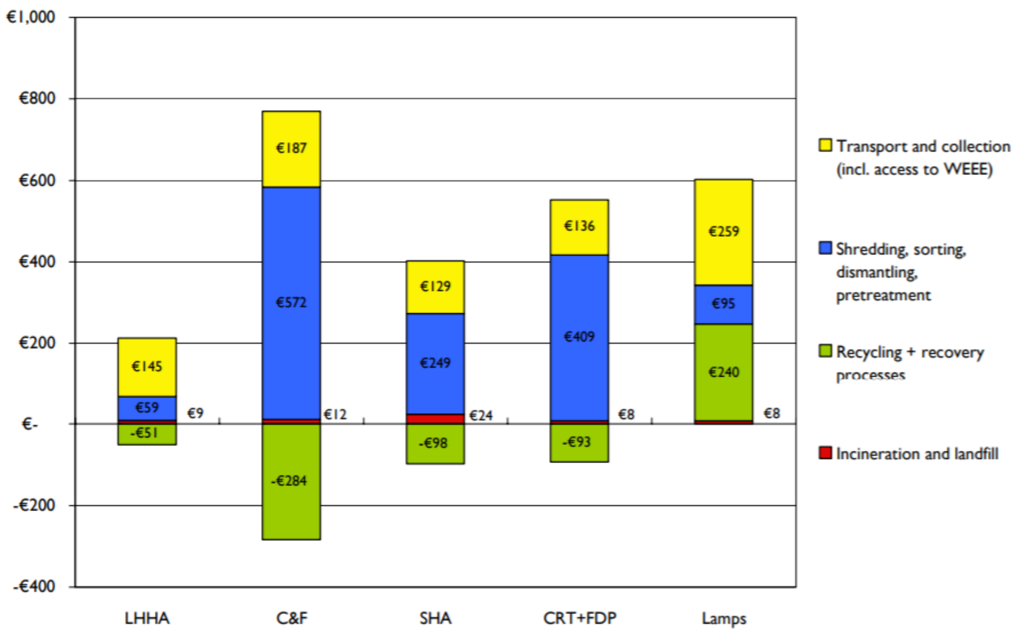

Figure 1.1: Technical costs for the 5 main categories in RL per ton in 2007 (Url-3).

Reverse Logistic Network can be designed for all production systems and products types. Sand, carpet, wood and electrical electronic (WEEE) products including white-goods, batteries, computers are the products that used to have included in a Reverse Logistic Network. WEEE is electronic equipment that comes to end of life and contain at least one electric electronic pieces or part. Electronic equipment accepts as a WEEE for more than one reason; it can be broke, it can become out of necessity for technological reasons or it seems as outdated. In Turkey, WEEE legislations are started to emerge with the process of the Turkey's membership of the EU.

In May 2012, the Ministry of Environment and Urbanism published the Regulation on Control of Waste Electrical and Electronic Equipment (AEEE) in Turkey. However it sets certain recycle targets to firms by product category, due to the lack of infrastructure, information and legal sanctions, it has been difficult to apply it. Now, in 2017, AEEE will be reviewed and the scope will be broadened with strict penalties.

In this thesis, white-goods, especially refrigerator returns are examined and proper operations planning are proposed. Based on the region distances and amount of waste, inventory and source requirements and waste collection decisions are tried to have evaluated under certain limits and constraints.

The purpose of this thesis is to develop a mathematical model aiming reducing the cost while maximizing the amount of properly disposed hazardous materials. A multi-objective, multi-product and multi-period MILP mathematical model for a reverse logistics firm was proposed.

1.1 Reverse Logistics

Cradle to grave resource management has been used to management the disposal of the chemical waste back in 1980's. It has now become the "cradle to cradle" with the evaluation, recycling and reuse of the wastes (Kumar et al, 2008).

With the increase in the both production and consumption in the globalizing world, rapidly increasing expectations make manufacturers business harder. With proportional to the increase in the demand, lifetime of the products are shortening. Customers prefer environmentally oriented products that are less harmful and dangerous. Environmental concerns that are considered in logistics are, nonrenewable resources, gas emissions, density and road use, noise pollution, destruction of both harmful and harmless wastes.

Development of third world countries led to increase in the consumption, so natural sources and raw materials are assumed to be vanished soon. Reusing these sources will gain new dimension to this problem. After WEEE and RoHS are implemented, wastes affected from these regulations about 70%.

In some developed countries, waste management and prevention are being pursued with legal legislations. These directives also puts obligations on issues such as how much the product should be recycled. It may also include disassembly manuals and part introductions (for ease of recovery and reuse).

Firms are collecting end-of-life products especially because of the legislations. Since the reverse logistics have complex structure and processes that are hard to implement, it is very challenging for the firms to make profit from reverse logistics. Establishing an efficient RL network in Turkey is very costly when considering the small amount of profit it brings. In Turkey, the periodically applied ‘bring old take new one’ campaigns are being implemented to increase the market share of the company, not to reuse or recycle the products. And since there is not any financial penalty in last AEEE, environmental obligations are also not very encouraging.

Most of the papers are written about the RL. Network design is one of the major subjects in RL due to its’ profitability. Logistic network have to be designed to optimize the process flow for increasing the gained value from used products. Therefore, it is separated from waste management. It contains, where and how these products are collected, how they are examined, how disposal is conducted for the scrap products, how and where the recovery processes are applied to the products that requires processing and the distribution of the recovered products.

However, other topics, such as, forecasting of the demand for return products, optimal transportation of the collected products and production planning of RL facility, which are not enough studied yet, may help to gain deeper understanding about RL and also provide developing proper recovery methods. Combining the RL with Operations Research will provide that. Operations Research aims to find effective ways to use not only the money and resources of production, also it can be used to optimize the usage of naturel resources (Dekker et al, 2012). Products' marginal value also has to be concerned; electronics are losing value by monthly or yearly. Products lost its marginal value in time, for example, computer loses its marginal value approximately 1% weekly. Therefore, decide to proper collection time is also challenging issue and requires interdisciplinary work.

Electronic waste (e-waste) is directly proportional with the country welfare level so countries like Norway and Switzerland whose internal revenues are higher are expected to 29 kg e-waste per person. In Turkey, this number drops to 6.5 kg .USA is the leader with 7 million tons of e-waste annually, following China with 6 million, and Japan with 2.2 million tons. Turkey is 17th with the 503 thousands of tons.

1.1.1 Reverse Logistics Returns

Products may return from different channels (Dekker et al, 2004; Kılıc, 2005);

Return from production:

- Raw material surplus (unwanted)
- Return from quality control (incorrect)
- Production residuals (unwanted)

Distribution Returns:

- Recalled products (or safety and health reasons)
- B2B (collection faulties / products that resend by distributor or retailers to the manufacturer or wholesaler if it is not sold)
- Inventory adjustments (especially seasonal items in warehouses and stores)
- Functional turns (distribution carriers)

Customers returning:

- Returns with warranty and refund
- Return from service (repair, spare parts)
- End of life products

1.1.2 Reverse Logistics from Different Perspectives

- Transportation aspect:

Trying to reduce the carbon emission is one of the popular subjects in OR. Choosing proper mode of transportation (plane, truck, ship, pipeline etc.) is critical if cost, quality and speed of transportation mode is considered. Between the transportation modes and facilities, complex coordination of material handling process occurs and with containers and new technological findings, this cost and time tried to optimize. Fuel is the biggest cost of the transportation and within different types of fuel, finding the appropriate, most environmental friendly and at the same time most effective one is hard challenge.

Type of products due to their volume while transportation:

1. Products that their volume does not change (book etc.)

2. Products that their volume decrease (plastic, etc.)

3. Products that their volume increase (such as PC)

- Product aspect:

Some products are more environmentally friendly according to their carbon footprint, the way that inventoried and remaining value after end-of-usage.

- Facility aspect:

With increasing popularity of the green facility and buildings, shortening the ways in the facilities and using electrical devices instead of fuel, using solar panels decreasing the usage of electricity and arranging proper waiting stations to vehicles.

- Supply Chain Aspect :

Products source(where they come from and the route they follow, How they transport and which facilities they visit and the production type and concepts) are the decisions that has to made and these decisions directly affect the productivity of the performance of the system . It can be easily said that, OR is very crucial for the environment because of the objectives that has to be satisfied under certain constraints.

1.1.3 Inspection and Treatment of Returned Products

Electronic products are not similar, some of them include hazardous materials and ingredients and some of them have very high residual value. They could not treated same, so especially product based recovery models are popular which are minimizing the processing time of the returned products (Dat et al, 2012). In Figure 1.2, WEEE treatment steps are shown. Different papers propose similar recovery steps and some of them are;

Fleischmann's recovery steps:

1. Collection

2. Inspection/separation

3. Re-processing

4. Disposal

5. Re-distribution

Bereketli et al (2011)'s recovery steps:

1. Reuse

2. Recycle

3. Disposal

Liu et al (2002) and He et Al (2006)'s recovery steps:

1. Re-use

2. Service

3. Re-manufacture

4. Recycle

5. Disposal

1.2) Reverse Logistics in Turkey

Turkey is a developing country with a population of more than 79 million. With a rapid development in technology, people want to follow the trends and buy more. Turkey is 17th in the world with 503 thousand tons of e-waste in according to "2014 Global e-Waste Monitoring Report" prepared by United Nations University (UNU). The amount of e-waste per person in the country was 6.6 kilograms. Some municipalities are allocated a special day for paper and electronic collection nowadays, however they are very few in numbers. People are informed various ways to describe the damage that e-wastes give around and the benefits that can be gained from these wastes.

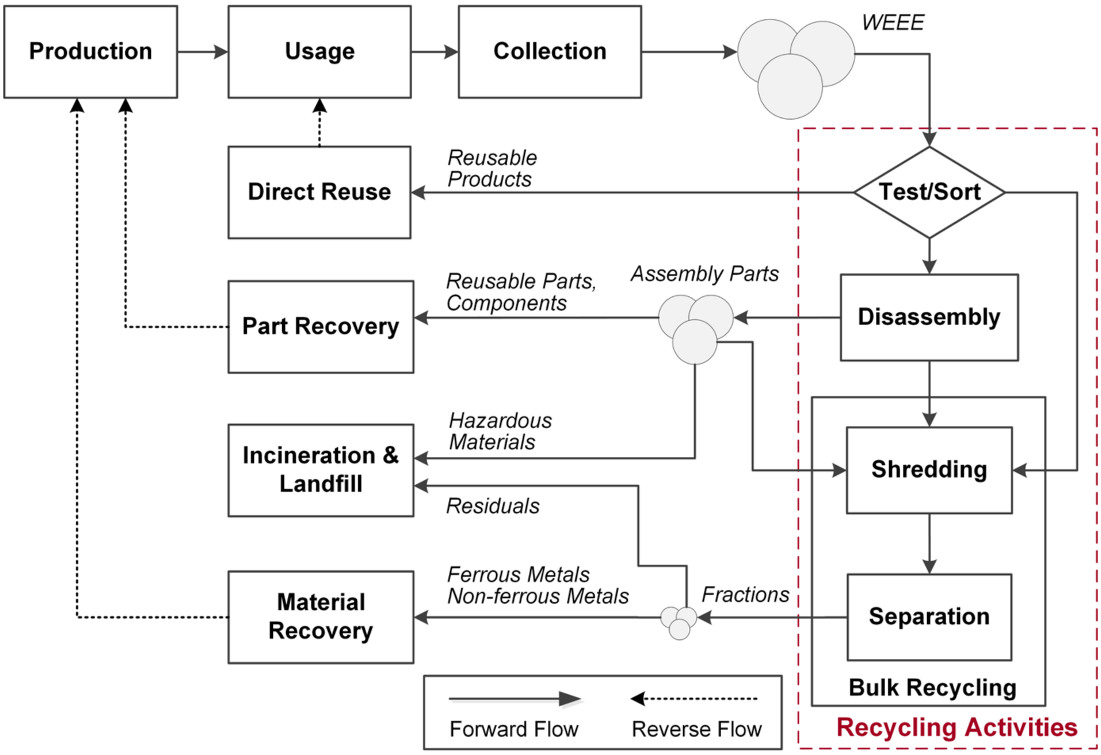

Figure 1.2: WEEE treatment procedure (Çapraz et al, 2015)

Reverse supply chain studies in the automotive, white goods, electrical and electronic and furniture sectors in Turkey have been examined (Erol et al, 2010).These 4 sectors were chosen because they are leading sectors. In the study 40 companies (40% are automotive, 25% are white goods, 15% are electrical-electronic and 20% are furniture) that are in the top 500 companies of the Istanbul Chamber of Industry (Istanbul Chamber of Industry). Data were collected using a semi-structured interview technique. 24 interviews were conducted with senior managers. According to the results of this study shows that RL is still at the beginning level in Turkey. The absence of legal obligations in this field slows down this process seriously. The biggest concern of the companies in this field is that they will not be able to deal with the returned products independently. The system says that there are disagreements and infrastructure deficiencies, which reduces the value obtained from the re-use of the products to a large extent. Almost all of the companies said that sustainability plays a key role in the present and possible RLND.

In Turkey, existing models are implemented to cases, nothing new proposed. There has to be new and unique problems should be modeled and solved (Gılanli et al, 2012). While designing the reverse logistics network; the first decision that has to be made by the Original Equipment Manufacturer (OEM) is to decide whether third party vendors or their own recovery channels will collect the end of life products. In Turkey, recycled materials are not using by the OEM’s; generally materials are sent to scrap firms.

Internal and external factors have effect on RL and firms have to follow required procedures. In Turkey lack of legislations and incentives are barrier for development of RL and firms have hesitation to implementing RL into their system because of the high cost and system necessities. However, as a result of some driven forces, most of the large scales firms have already formed their RL network.

Driven Forces for RL:

1. Economy

Many developed countries putting legislations to increase the turned and remanufactured amount of used products. Other developing countries are also working on these types of legislations. Being prepared for these legal obligations in advance is a step that can provide superiority to other firms.

Increasing the firms’ image can be one of the indirect contribution of the RL. Direct and indirect incomes, materials that obtained for further usage, cost reduction in energy are the economic gains. Value-added improvements are the other economic benefits.

2. Legislations

There has to be legal legislations to force the firms. With obligations, public should be made aware of the importance of the collection of recyclable resources. Legislation will set certain standards and companies will have to follow up on collection, disposal, recycling, and marketing their products.

In Turkey, with AEEE some companies have begun their recycling works. Many of the companies will have to be included in these activities because the penalties will come with the new AEEE revision soon.

3. Environmental Concerns

Minimizing the negative impacts of waste, proper management strategies should followed. With reusing, recycling and remanufacturing the WEEE, social environmental benefits are obtained at the same time. In addition, green image that reflected and advanced customer supplier relationship is profitable for firms.

Handicaps of RL implementations in Turkey;

1. Problems related to product quality (customer assumed that remanufactured products or recycled materials could have lower quality) and it is thought that it will effect firm prestige. People should be informed about the remanufactured products are not different from the original product and they have guarantee, and suitable for all usage purposes.

2. Deficiencies in information system and technological infrastructure.

3. Lack of interest from upper managers.

4. Lack of knowledge about legislations (Erol et al, 2010).

5. Lack of information and technology. Therefore, the need for labor source is high. In addition, product ingredients cannot known exactly because firm policies or some other reasons. In addition, most of the products are hard to disassembly since most of them produced without considering recycling and remanufacturing.

What can be done in the future (Kumar et al, 2008);

1. Obtaining economic efficiency in converting technology, in collecting, dismantling, recycling

2. Improving the recycling technologies

3. Opening a second market and market for the converted materials

4. Developing advanced information network along closed network

System uncertainties should take into account. Existing models applied to industries in Turkey; however, there is not new model proposed. Unique features and problems in Turkey's reverse logistics should be modeled and original solution methods should developed with regarding to these findings (Akyıldırım&Abdildaev, 2016). Uncertainties in the RL nature makes calculations difficult but gives the right results if they are taken into account. Papers that consider uncertainties in Turkey; Subulan in 2015, in 2013 Ayvaz and Bolat proposed SAA, Doğan and Kırda (2014) proposed genetic algorithm and ANP and Fuzzy-Topsis methods are proposed by Tuzkaya et al, 2011.

1.3 Capacity Planning in Reverse Logistics

Material and capacity planning and control constitute the two key points of production and should be coordinated properly for maximum benefit. Estimation of capacity requirements in capacity planning is the most important point in terms of meeting future demands. The other point is that these plans are implemented smoothly considering the negative situations that may arise.

How to do capacity planning?

- After determining the resource requirements, the capacity planning for the MPS should done.
- A medium-term plan is set up for detailed material planning.
- Then moves to the short-term planning; Scheduling and capacity trade-offs and assessment of plans should done.

In the last few years, short-term planning is new trend because it provides faster respond to demand with less inventory.

There were three major techniques commonly used for RCCP:

- 1.The Bill of Resources approach;
- 2. Capacity Planning using Overall Factors (CPOF) approach; and
- 3. The Resource Profiles approach.

These traditional techniques are possible candidates for use in remanufacturing environments. (Guide JR. et al, 1997)

Capacity planning is harder than in traditional capacity planning since it is hard to forecast product's lifecycle, lifetime and after taking back the quality of the returned product (its reusability , re-manufacturability and disposal rates). There are many techniques are proposed in capacity planning in forward direction of supply chain. However, there has to be new models and suggestions in reverse logistics to manage the uncertainties. Size of the models and uncertainties that has to be taking into account make problem solving longer and harder. Lembke (2002) proved that lack of study on product returns and remanufacturing are the reasons for this problem

Correct forecasting have important role to increase the efficiency. Georgiadis & Athanasiou (2013)'s study investigates long-term capacity planning in RL and CL including uncertainties in operational environment and high capacity purchasing cost and concluded that combination of small but frequent capacity expansion provides minimizing the profit lost with policy efficiency. Increasing the capacity is an alternative however; it caused lots of margin declines and even losses.

Especially the actors whom have social responsibilities are led to involve the Reverse Logistics. Products lifetime and the pattern they follow, residence index are considers as uncertain and related entries. According to Sudarto et al's study in 2016 there are three findings;

- Product's usage period, unknown reusability, the breakdown rate, and the recycling rate of the used products are not predictable in advance, so capacity planning in RL is much more complex than traditional one.
- The fund investment on social responsibility could create a green image, so drive an increase in the demand.
- The performance on the environmental dimension is affected by the policy parameters with various effects and powers of significance.

If social responsibilities included in RL, Reverse Logistics Social Responsibility (RLSR) emerges. Capacity planning in RLSR has additional constraints compared to general reverse logistics. In addition, with taking into account the interconnected sustainability dimensions of the RLSR that produce a unique relationship between sustainability dimensions, uncertainty and Policy. For this reason, capacity planning in the RL is much more than an easy problem.

2. LITERATURE REVIEW

In this chapter, first the literature on reverse logistics models and practices reviewed. Then, single-objective and multi-objective models are mentioned respectively .In order to produce scientific solutions to environmental problems, different disciplines must brought together and solutions should be produced. When it comes to the benefit in the RL, it requires a disciplinary study, considering both economic, environmental and social objectives together.

Hu et al. (2002), systematical management strategy proposed for hazardous waste reverse logistic system and both external and internal factors taken into account as a distinctive feature in the literature. The proposed cost minimization model is multi-time-step and multi-type waste.

In Widmer et al. (2005)'s study, e-waste types are defined and legislations and incentives are mentioned to increase the amount of turned e-waste. E-waste estimation methods explained as Lohse et al.'s techniques; 1.consumption and use method market supply method, Swiss Environmental Agency's Estimation method and an additional method of Matthews et al's technique that is based on sales data.

Kumar et al (2008) analyzed closed loop supply chain with SWOT analysis, especially in the successful industry segments (automotive, consumer appliances and electronic) and examine the effect of the legislations upon them.

Erol et al. (2010) have examined electrical electronic and furniture sectors in Turkey in 2010. Some of the studied problems are; reasons for accepting product returns, factors that consist handicaps for successful RSCM, legislations and firms awareness level of this subject, outsourcing reasons and preferences.

Contributions of OR to the green logistic is mentioned and discussed with lots of aspects ; transportation, products' and inventories lifecycle ,facilities, supply chain design and planning by (Dekker et al ,2011).

A comparative classification study in Turkey is conducted, reverse logistics articles have been examined and classified according to their topics. RL network design is the most studied subject, however it is seen that there is not enough study on estimation of demand, ideal recovery methods and transportation strategies of returned products that also considers uncertainty. According to Akyıldırım&Abdildaev (2016), there is not much work done in Turkey, especially considering the special situations of the country. Reverse logistic activities in Turkey are examined by survey conducted in Thracian region in the Gilanli et al.'s study in 2012.

2.1 Single-Objective Models

Deterministic and then stochastic MILP location-allocation problem proposed by Listes&Dekker in 2005 and two-stage and three-stage solution approaches applied and compared with the deterministic model. In this study, previous studies on sand recycling problem extended based on developing available technology. With taking the uncertainties in demand and quality, deterministic model turned into stochastic model and more realistic problem obtained. Listes again, in 2007 proposed generic two stage closed loop supply return network model and decomposition approach based on L- shape method used. The proposed deterministic MILP model aims to maximize the net revenue and solved with the stochastic approaches. El-Sayed et al. (2008) proposed single objective, multi period multi echelon closed loop supply chain model and effect of demand mean and return ratio changes evaluated. Problem formulated with Stochastic Mixed Integer Linear Programming.

According to Pishvaee it is hard to decide the capacity of the recovery and recycling facilities. Furthermore, there could be incentives that encourage customers to take back to their products. For this reason, capacity and repurchase prices are also decisions that need to be made. Giving customers to incentives directly influence the company's reverse logistics profit. Since MIP is insufficient to present system dynamics, they used System Dynamic approach so with sensitivity analyses, they compared the effect of change in the parameters (Pishvaee et al, 2009a). Pishvaee et al (2009b), again, modeled the system as deterministic and adding uncertain variables they turned into the stochastic model with 3 uncertainties. In this model, quantity and quality of returned products and demand for this product are assumed uncertain, stochastic MILP model for single period, single product and multi-stage closed loop logistics network design is developed and used Scenario-approach to solve it.

Kannan et al (2010), created multi echelon, multi period, multi product closed loop supply chain network model for product returns. Material flow, recycling and disposal of wastes examined to make decisions and heuristics based genetic algorithm (GA) is applied as a solution methodology to solve mixed integer linear programming model (MILP).

Dat et al's model in 2012, optimize reverse logistic costs for recycling end-of-life electrical and electronic products. Single objective, deterministic, multi product WEEE model proposed, previous researches extended to model a more complete recycling network with various treatment sites and final sites for multiple types of WEEPs including multi-stages; three collection sites, three types of final sites, primary market ,secondary market, and disposal site, three disassembly.

In Donmez&Turkay's (2013) study, model offers different capacity options, capacity increase option for plants, sale of recycled metals to second-hand market, fixed and variable costs for plants.

Yanık (2015) is proposed a network design model with forecasting of returned product. In this study, network for reverse logistics designed almost from the scratch, return amount of product is forecasted, risk model created for hazardous materials, and capacity limited facility location model under risk proposed. For forecasting the returned amount, mostly affecting criteria detected and with multiple linear regression model used. Other than logistic regression, simulation models and time-series analysis are also used for accurate forecasting.

For forecasting problem, most of the papers take just few of the effecting factors into consideration, however all criteria that could have affect the amount should have considered. Kılıç et al. (2015) offered a MIP model for RL Network Design in Turkey, scenarios are proposed based on recycling rates, so that minimum WEEE requirements provided. Suitable (automatic or manual) facility type and allocation decisions are made with these results.

2.2 Multi-Objective Models

Pishvaee et al in 2009 mentioned that network cost and response level is gaining importance in reverse logistics. In this bi-objective nonlinear network design model linearized by defining a variable and adding a constraint. Model solved with a multi-objective memetic algorithm with dynamic local search mechanism (MOMA) and the multi-objective genetic algorithm (MOGA) used respectively and results compared.

Tuzkaya et al. (2010) have proposed a model with two objective functions and an application in white good industry in Turkey. First objective function aims to minimize the net cost, which consist of transportation cost, ICC rental, and installation cost, retention, inspection, classification, disposal and maintenance costs minus revenues gained from recycled products. Second objective function intend to maximize the amount of weighted product assigned to CRCs (centralized return centers) from ICC's (initial collection centers).This model is constructing a framework by including lot of cost parameters. The proposed methodologies for this model are Genetic Algorithm and integrated MCDM-GA methodology as a unique approach to the problem.

Multi-time-step multi-objective decision-support model proposed aims minimizing cost, environmental risk, socially perceived risk and health risk at the same time and deciding the optimum locations considering existing ones by (Ahluwalia&Nema, 2011).

With defining uncertain parameters, models that are more flexible can be formed so they can present real-world problems better. In Ramezani et al. (2013)'s model different parameters such as (price, production costs, operating costs, collection costs, disposal costs, demands and return rates) are assumed to be uncertain. E-constraint method used to generate to set of Pareto-optimal solutions for solving this 3-objectived problem. Objectives of the model are maximizing the total profit, maximizing the customer service level and minimizing the defected products that are provided by suppliers.

Bi-objective, single period, non-linear model reformulated as MIP by linearization by Wang et al in 2011. Environmental protection level described for the first time in the literature. Model aims to minimize total cost and total CO_2 emission all in the supply chain. Normalized Normal Constraint Method proposed by Messac used to provide evenly distributed Pareto solutions by giving evenly distributed scalar weights. A closed loop facility location model is proposed (Amin&Zhang, 2013) in supply chain network with multiple facilities and multiple products. This mixed-integer linear programming solved weighted sums and e-constraint methods and show that e-constraint method gives solutions, which are more efficient. After uncertainties in demand and returns taken into account, it is solved with stochastic programming (scenario-based).

A new multi-objective MIP model proposed for location-routing model with three objective functions by (Samanlioglu, 2013). Objectives are minimizing total cost, total transportation risk of hazardous materials and site risk.

2.3 Reverse Logistics Literature Table

In the table below (Table 2.1), reverse logistics literature is briefly discussed.

Table 2.1: Literature table.

Author&Date	**Type**	**Objective (Single-Multi)**	**Deterministic-Stochastic**	**Solution Method**	**Aim**	**Product-Stage**
Hu et al, 2002	discrete-time linear analytical model	Single objective	Deterministic model	Lindo software package	Cost Minimization	Multi-time Multi-Product
Listes&Dekker, 2005	MILP	Single objective	Stochastic model	Two-stage and three-stage solution	Maximizing the net revenue	Multi-time Multi-Product-multi stage
Listes,2007	MILP	Single objective	Stochastic model	Decomposition approach based on L-shape method	Cost Minimization	Multi-time Multi-Product-multi stage
El-Sayed et al,2008	Stochastic MILP	Single objective	Deterministic+ stochastic model	Multi-stage stochastic program	Maximization of the total expected profit	Single objective ,multi period multi echelon
Pishvaee & Shakouri G.,2009	MILP	Single objective	Deterministic model	System Dynamic approach with sensitivity analyses	Capacity planning and price adjustment problem	Single period, single product, multi-stage
Pishvaee et al,2010	MILP	Single objective	Deterministic+ stochastic model	Scenario-approach	Forward/reverse logistics network design	Single period, single, multi-stage product

Table 2.1 (continued): Literature table.

Author&Date	Type	Objective (Single-Multi)	Deterministic-Stochastic	Solution Method	Aim	Product-Stage
Ahluwalia& Nema,2011	MILP	Multi-objective	Stochastic model	Lingo software package	Minimization of environmental risk, socially perceived risk and health risk at the same time	Multi-time-step, multi period, multi echelon
Tuzkaya et al,2010	MILP	Multi-objective	Stochastic model	Genetic Algorithm and integrated MCDM-GA	Minimization of net cost and maximization of the amount of weighted product assigned to CRC from ICC	Multi-time-step, Single period multi echelon
Kannan et al,2010	MILP	Single objective	Deterministic model	Heuristics based genetic algorithm (GA)	Cost Minimization	Multi echelon, multi period, multi product
Dat et al,2012	Linear Programming	Single objective	Deterministic model	Sensitivity analysis	Cost Minimization	Multi product, multi stage
Du&Evans,2008	MIP	Multi-objective	Deterministic model	hybrid: scatter search& the dual simplex method and the constraint method	Cost Minimization and minimization of total tardiness of cycle time	Multi product, Single period

Table 2.1 (continued): Literature table.

Author&Date	**Type**	**Objective (Single-Multi)**	**Deterministic-Stochastic**	**Solution Method**	**Aim**	**Product-Stage**
Wang et al,2011	Non-linear model	Multi-objective	Deterministic model	Normalized Normal constraint method	Cost Minimization and total CO_2 emission	Multi facilities, multiple product, Single period
Ramezani et al,2013	MILP	Multi-objective	Stochastic model	Multi objective Є-constraint method	Maximizing the total profit, maximizing the customer service level and minimizing the defected products	Multi-echelon
Samanlioglu, 2013	MIP	Multi-objective	Deterministic model	Lexicographic weighted Tchebycheff formulation	Minimization of total cost, total transportation risk of hazardous materials, site risk	Multi-stage, multiple product,
Amin&Zhang, 2013	MILP	Multi-objective	Deterministic+ Stochastic model	Weighted sums and e-constraint methods (scenario-based)	Maximizing clean technology usage Cost Minimization	Multi facilities and multiple product
Pishvaee et al,2010	MINLP	Multi-objective	Deterministic model	(MOMA) (MOGA)	Network cost and response level	Multi-stage, multiple product, multi period

Table 2.1 (continued): Literature table.

Author&Date	**Type**	**Objective (Single-Multi)**	**Deterministic-Stochastic**	**Solution Method**	**Aim**	**Product-Stage**
Donmez, & Turkay, 2013	MIP	Single objective	Deterministic+ stochastic model	GAMS-CPLEX	Cost Minimization	Multi-echelon, multi stage, single product
Darbari et al,2016	MIP	Multi-objective	Deterministic model	Goal Programming	Maximize Profit & Minimize Carbon Emission	Multi-echelon, multi stage

3. WHITE-GOODS INDUSTRY AND RECOVERY OF THEM REGARDING WITH THE LEGISLATIONS

Although reversing the supply chain is possible, there are obstacles when integrating the knowledge of supply chain management into take-back processes because of the uncertainty in the composition and amount of the returned product. Different perspectives emerged combining facility location planning and vehicle routing problem (integrated approaches) by taking the age, condition of the product into consideration.

The foundations of the Turkish white goods industry were laid in the 1950s. In these periods when the domestic industry is still in the installation process, due to technical possibilities and limited demand, production was very low.

Until the 80's most of the components of white-goods were imported. Because of the rise in foreign exchange, domestic producers started to produce these goods in order to offer a solution in this market. Consequently, domestic industry share in component industry for production increased. With investments on the R&D in early 90's, Turkish white-good industry become an independent market and gain competitive advantage among world market. White good companies operating in Turkey are investing heavily in ARGE (Research and Development), and in this regard, companies have the power to compete in the world.

Over the last 10 years, the improvements in energy efficiency of products reached 65 percent. The sector of white good industry employs 40 thousand people directly and 500 thousand people in total. While China is the world's largest white goods producer, Turkey is the second largest producer in the world and the biggest producer of white goods in Europe by 2014. Worldwide refrigerator imports totaled $ 17.7 billion in 2014, after the United States, ranking first with 26%. When it comes to refrigerator sales, Turkey is the fifth biggest country in the world in 2014, for refrigerator exports. In Figure 3.1 and 3.2 annual domestic sales and annual production number of white goods are given for six major categories.

It is estimated that the size of the world white goods market is to 185 billion dollars with an increase of 2.4% in 2014. The production of white goods in Turkey in 2015 increased by 8.7% compared to the previous year, reaching 24.6 million units. 75 % of the production in the sector is exported to about 150 countries and the most important export market of the sector is EU countries given in Figure 3.1 and 3.2. Domestic white good sales increased by 5.7% compared to the previous year and reached 7 million units in 2015 (Table 3.1). As of the end of 2016, while exports were 19.54 million units in 8 main sectors, 8% over the previous year, domestic market reached 7.46 million units with 5% growth.

Table 3.1: White good domestic sales and production rates in 2015.

Year2015	Domestic Sales	Annual Change	Production	Annual Change
Washing Machine	2026292	6,8	7466366	18,4
Refrigerator	1976199	3,6	6833284	2,6
Dishwasher	1483435	3,4	3608652	3,6
Oven	951231	9,6	4365929	2,8
Freezer	571160	6,7	1037973	7,8
Dryer	81734	26,9	1250929	337
Total	7090051	5,7	24563133	8,7

The growth of the sector is driven by the increasing urbanization in Turkey, the young population and the movement in the construction sector as well as developments in the export markets, especially in the EU countries. Factors determining the demand for white goods in Turkey:

- Marriages
- Divorces
- Young population

•	Building permits: Increased urbanization rate and mobility in the construction sector are influential in the growth of the market.

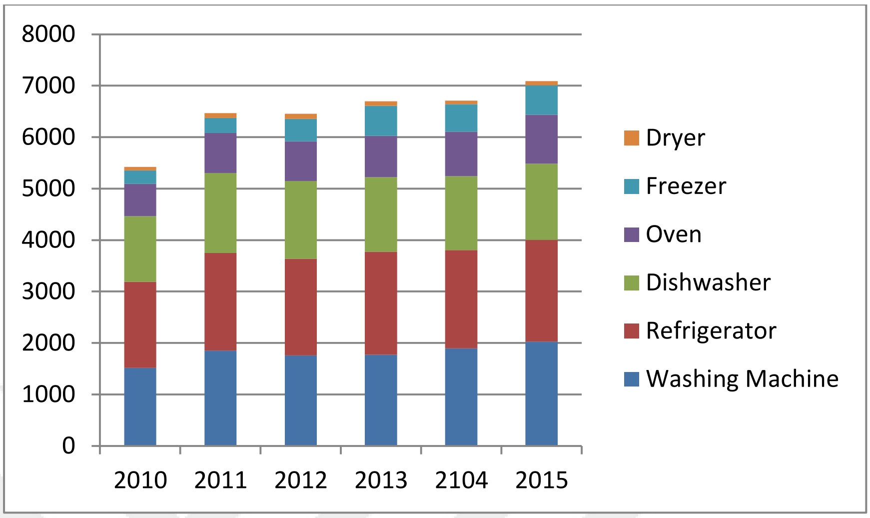

Figure 3.1: Annual domestic sales of white goods (thousand).

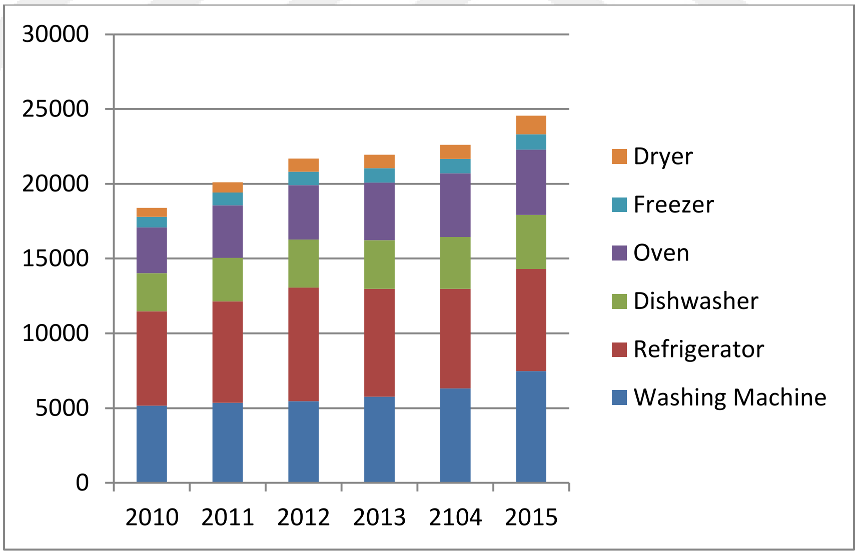

Figure 3.2: Annual domestic production of white goods (thousands).

Association of Turkish white goods producers (TURKBESD), expect to sales of white goods reach 7 million in domestic and 19 million in exports in 2017.

The Waste Electrical and Electronic Equipment (AEEE) Regulation has entered into force, but implementation has not yet begun, and the investments may be negatively affected if necessary precautions in controlling imports and market are not taken. The

AEEE Regulation applies to all types of household appliances, electronic devices, televisions, computers, electrical appliances, etc. that have come to end of their lives. This regulation contains the collection and recovery of these products, evaluation of them without giving any harm to the environment with management strategies in all steps. This process gives significant financial burdens for both producers and importers. In the implementation of the directives such as AEEE (Waste Electrical and Electronic Equipment) which are not completely structured, government should not be rush. There are countries that are not yet implemented WEEE in EU countries even quite time passed. The Ministry of Environment and municipalities must complete these necessary infrastructure works, and assign free collection areas and ensure beneficial organizations.

3.1 Legislations

3.1.1 WEEE

This legislation, limits the certain type of hazardous materials and substances in electrical-electronic products in EU market. In addition, EEE's environmental impact wanted to be controlled. Aims of the WEEE Directive are;

- ✓ Reducing the waste generated by EEE,
- ✓ Enhancing the recovery rates
- ✓ Improving the environmentally conscious involvement of all the participants through EEE's life cycle.

WEEE covers all electrical-electronic equipment that are used for both personal use and professional use. These are gathered in 10 categories as follows;

1. Large household appliances

2. Small household appliances

3. IT and telecommunications equipment

4. Consumer equipment

5. Lighting equipment

6. Electrical and electronic tools

7. Toys, leisure and sports equipment

8. Medical devices

9. Monitoring and control instruments

10. Automatic dispensers.

WEEE’s scope is producers, distributors, consumers and all partied involved in the collection and treatment of WEEEs. WEEE set certain targets and goals to achieve over by per inhabitant, which changes region to region, and put penalties for firms that could not reach expected rates.

WEEE’s that are generated by developed countries are transferred to the developing countries illegally and value of these waste is unknown.

Under the Revised WEEE Directive, by 2016, there is a collection of 45 tons of e-waste for every 100 tons of equipment sold for 3 years. It is aimed to increase this ratio to 65% by 2019.That is, it is aimed to collect 85% of the emerging e-waste.

3.1.2 AEEE

In May 2012, the Ministry of Environment and Urbanism has issued the Regulation on the Control of Waste Electrical and Electronic Equipment (AEEE) in Turkey.

In the directions of the regulation, the producers either collect and return the old products themselves or make them to send an authorized institution. The state is not fully prepared to direction because it is a new process in Turkey; there are deficiencies in infrastructure and organization.

If company wants to implement their own recycling;

Old products collected by authorized services are sent to licensed recycling plants by Supply Chain departments. All transactions in the process should have monitored with the software of the company.

Benefits obtained by recycling good products are;

- Materials such as plastic, iron, copper, which are obtained from electronic waste, are sent back to the firm to be reused or as scrap so that the economy is restored.

- Harmful gases collected from the waste are collected and prevented from being released into the atmosphere.
- Uncontrolled sale of second hand products and parts in the market is also prevented.
- In addition, energy-consuming old products are collected, reducing the electric power consumption of the country.

3.2 Waste Management

Waste management is one of the major ways to maintain sustainability. WEEEs contribute the greatest opportunity with a number of (from 20 to 50 million tons are globally generated each year) with increasing rate of 3-5% a year. Also correct amount of incentives for users to give their end of usage products, increase the number of returned products. Trying to decide the optimal incentive value for both manufacturer and costumer is useful although is a challenging issue (Kaya,2010).It is important to explore both cost effective and environmentally-friendly recycling techniques to contribute both firms and environment. Mechanical recycling of WEEE (Güngör&Gupta, 1998; He et al, 2006) follow these steps;

1. Disassembly:

Process that helps to remove part or group of parts by partially or completely such as cables, plastic and valuable parts. So that latter recovery processes can handle easier. This process can have conducted by manually or automatically. The type of refrigerator does not matter during collection. However, during disassembly, refrigerators are separated by the type of refrigerants.

2. Upgrading:

Effectively separating the product according to constituent materials features

1. Comminuting: Changing the product’s size into proper and smaller dimensions (granulated) by shredding.
2. Separation: By magnetism, electrical conductivity and density of the product, materials separated. Especially ferrous and non-ferrous materials are decomposed. Eddy-current separation, corona electrostatic separation, and

triboelectric separation are the techniques based on the material’s electric conductivity.

3. Refining

After these processes, recovered materials return to market. Cold-refrigerators and freezers are evaluated separately from white goods because of their contents. They may contain refrigerant gases such as Ozone Depleting Substances (ODS), such as chlorofluorocarbons (CFC), hydro fluorocarbons (HFC) and hydro chlorofluorocarbons (HCFC) which are now banned in many countries. The WEEE Directive forces the removal of all fluids from WEEE. Fluids must have safely removed before to recycling operations. Refrigerants (fridges and freezers) – most refrigerators come to end of life between 10 and 15 years and are therefore likely to contain Ozone Depleting Substances (ODS) (e.g. CFCs and HCFCs) because they are manufactured before 1994(3).

Compressors are separated from refrigerators and decontaminate, metals are sold and plastic and other materials can be sold or reused. Oils and gasses that are extracted from the products are sent to licensed disposal firms for proper disposal.

4. MULTI-OBJECTIVE PROGRAMMING, EPSILON CONSTRAINT METHOD AND AUGMECON METHOD

4.1 Multi-Objective Programming

Today's problems require satisfying more than one objective. To simplify, it several objectives combined into one objective in problems. Cost is generally preferred way to link the objective functions, by combining all cost and income objectives into one objective by adding or subtracting them. However, in some optimization problems, it is not possible to find a way to combine the objectives since some of the objectives are qualitative and some of them are quantitative. In multi-objective problem, optimization gives solution that is acceptable for all objective functions. All the multi-objective optimization techniques involve a tradeoff between different objectives. MOP is used in different disciplines like engineering, logistics planning, economics in which more than one objective needed to be satisfied. However, optimizing all the objectives at the same time cannot be possible due to objectives' contradictory nature and restricting values of the problem. Instead of that, there are solutions called Pareto Optimal or nondominated solutions obtained, which cannot be improved without changing other objectives for the worse.

From that point, engineering decisions required to determine the priority of the objective functions. (Sunar&Kahraman, 2001) Instead of a single solution, trade-offs are find.

Multi-objective optimization is an optimization problem with a set of objectives, often inconsistent with each other.

$$\max z = \{c^1x, c^2x, \dots, c^rx\}$$
$$Ax \leq b$$
$$x \geq 0$$

Where $c^1, \dots, c^r$ are a set of objective vectors.

4.2 Multi-Objective Programming Solution Techniques

According to Hwang&Masud (1979) the methods for solving MMP problems can be classified into three categories according to the phase in which the decision maker involves in the decision making process expressing his/her preferences: The a priori methods, the interactive methods and the generation or a posteriori methods.

Table 4.1: Multi-objective solution techniques

Priori methods	• Contain less information for Decision Maker • Decision Maker sets goals or by weight, the objective functions prior to the solution. • Only one solution is provided at the end. • Disadvantage: Knowing the limits beforehand cannot be easy. Decision makers may not accurately determine the boundaries; therefore, so distant solutions can be obtained from Pareto Optimal Solutions.
Interactive methods	• Hybridize the priori and posteriori methods in which the decision maker's preferences is periodically refining to obtain efficient solutions leading to guide the search space more efficiently. • Decision Maker always interacts with the solution and includes the process to make choices at each iteration. • First, solution initialized, define a point given by DM or obtained by using some no-preference method. Aspiration levels and required generated number of solutions are determined. After that, new Pareto Optimal solutions generated and presented DM to select among them. • Iterative solution is produced and this process is repeated several times.
Posteriori(generation) methods	• Give all details about alternatives to decision maker for final decision. It is hard to compute so hardly use. • All efficient solution alternatives generated and decision maker select one of them (most suitable one). • Mostly preferred method because it is less subjective.
Evolutionary algorithms	• Typically generate set of solutions • Disadvantage: Lower speed, solution may not give real Pareto optimal solution • Evolutionary algorithms approximate the Pareto front and give information about the problem. • If there is little information, evolutionary algorithms is good alternative.

Other methods used in the multi-objective programming;

- ✓ Normal boundary intersection
- ✓ Method of weighted matrix
- ✓ Tchebycheff Method
- ✓ Light Beam Search
- ✓ Geoffrion-Dyer-Feinberg (GDF)
- ✓ MOGA
- ✓ NSGA and NSGA-II
- ✓ SPEA and SPEA2 ,PAES, PESA

4.1 AUGMECON(Augmented e- constrained) MIP model

Here epsilon (e- constraint) and AUGMECON (augmented e-constrained) modeling will be explained.

As in most cases, there are many alternative solutions, not a single solution, where some of the objectives conflict. Not all objective functions can improved at the same time but alternative solutions are created and such potential solutions are called efficient (Pareto optimal) solutions. In order to overcome these difficulties, an e-constraint method was proposed, in which only one goal was optimized, others were constrained by a specified coefficient (Torabi et al, 2010).

The e-constraint method was first proposed by Haimes et al. in 1971 (Zhang&Marc Reimann, 2104). In this method, one of the objective functions is selected to be optimized while the others are restricted with specified values so that it provides minimum requirements.

Idea of the traditional epsilon-constraint method is to iteratively increase the constraint bound by a pre-defined δ constant (Laumanns et al, 2006)

Advantages:

- Efficient solutions can be obtained.

- With using different epsilon values, different praetor optimal solutions can be found.
- This method can be used for non-convex multi-objective problems.

Disadvantages:

- Weakly efficient solutions are produced.
- Selection of the epsilon vector is crucial because of the solution is heavily depend on it. Each objective functions' minimum and maximum values should find and value between them is calculated.
- As the number of objectives increase, more information from the user is required and solution time is increased if more than two objectives exist.

If series of models want to solve with an optimization software, generally solutions that are found are not efficient .The AUGMECON method has been proposed by Mavrotas (2009) in order to avoid this shortcoming of the traditional constraint method (Zhang&Reimann, 2014) so that efficient solutions was guaranteed.

An improved version of the original e-constraint method with weighting method, one of the two most popular methods for producing pareto front.

In the epsilon-constraint method, each single-objective model is solved in a virtual grid space which are predefined in the objective space. If these grids can be determined correctly, model can be solved in such a way that there is only one Pareto optimal result within each grid cell. Therefore, determining this grid size is critical, as it is both difficult and time-consuming to solve the algorithm. (Laumanns et al, 2006)

4.2 Implementation of AUGMECON method

In order to avoid any scaling problems, instead of using s_i, s_i/r_i is used .r_i is the range of the objective function here.

Early exit is provided from nested loops when problem becomes infeasible, accelerates the solution of the algorithm.

By introducing slack or surplus variables, (Mavrotas, 2009) proposes transforms objective function constraints into equalities . These slack or surplus variables force the model to produce only efficient solutions where *epsilon* is a small number (usually between 10-6 and 10-3) (Mavrotas, 2009). (Bootaki et al,2014)

The first step in applying the AUGMECON is to construct the payoff table using the lexicographic optimization (Torabi et al, 2010) Lexicographic optimization is proposed for each objective function to construct the payoff table ensuring to yield not weakly efficient but just Pareto optimal solutions.

First objective function is optimized without considering other objectives. After restricting first objective function with previously find optimal value, second objective function is optimized. After that, adding first and second objectives optimal value as constraints, third objective is optimized.

For a bi-objective model, we should calculate the best (ideal) and worst (nadir) values of objective functions over the feasible space. The best value could be calculated as the optimal solution of individual optimization however the worst value is estimated from the payoff table (a table that is comprised of the results of individual optimization of objective functions). For constructing the second row of payoff table, the second objective function is optimized over the feasible region and the first objective is optimized with the adding second objective function and previously found value as constraint. For second objective, range between max and min value calculated and divided into certain p-1 number so that equal p -1 interval and p grid points are found. For each value of second objective function, first objective function is optimized.

If objective function is more than two, nested loops may be need. If problem size gets bigger, computation time gets longer. In order to avoid it, heuristic or meta-heuristic solution methods should have developed.

Algorithm of iterative calculation of AUGMECON is presented in Figure 4.1.

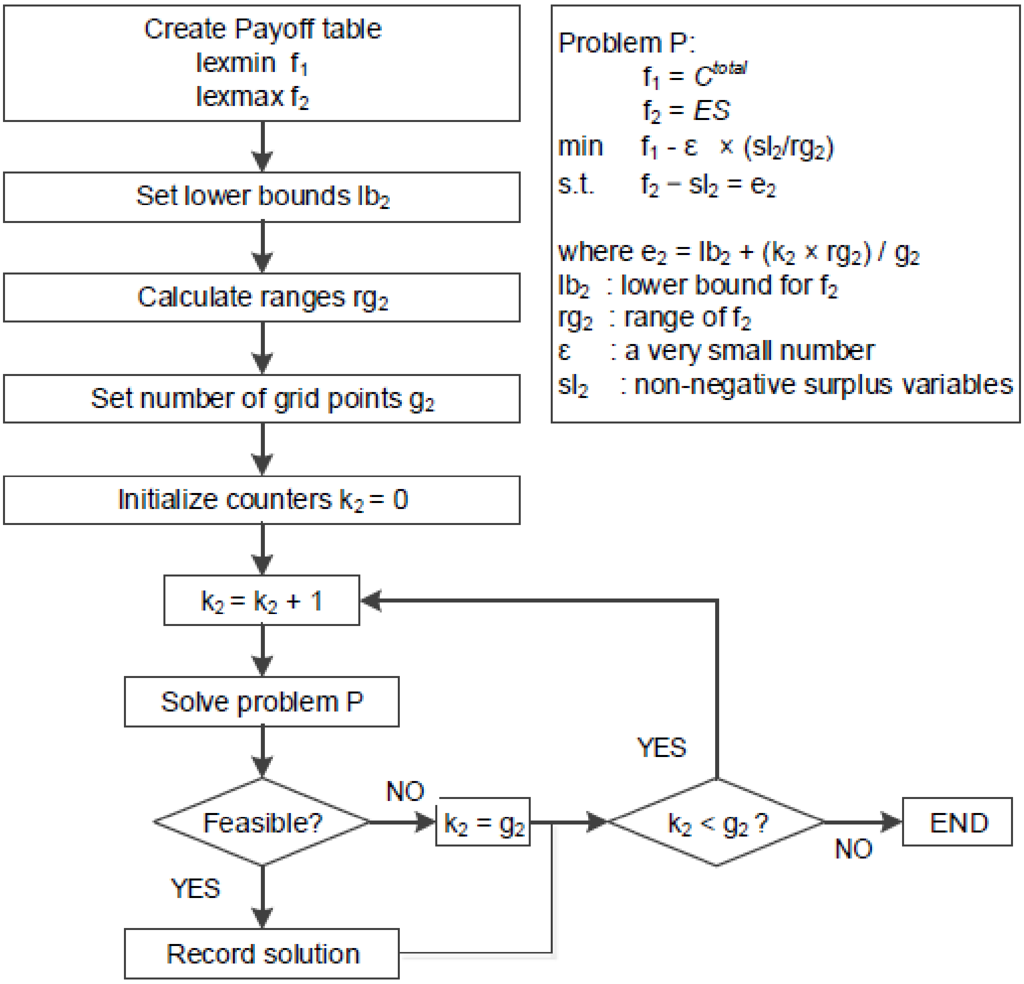

Figure 4.1: Algorithm of iterative calculation of AUGMECON (Sai et al,2010)

Example problem and solution with AUGMECON:

<u>Objectives</u>

objective1=x1;

objective2=3*x1+4*x2;

<u>s.t.</u>

x_1=20;

x_2=40;

5*x_1+4*x_2= 200;

The first objective is solved before the second objective is added and Objective1 = 20 is obtained. By adding the Objective1 = 20 as constraint to the model , and neglecting the first objective function, second objective is maximized and found as 160.

The same process is repeated for Objective 2, and Objective 1 is maximized with neglecting the second objective and found as 184. Value founded, Objective 2 = 184, added as constraint to the model, then Objective1 = 8 found , and the payoff table is created with these values.

Table 4.2: Payoff table of small AUGMECON implementation example.

Payoff Table	Objective 1	Objective 2
Max Objective 1	8	160
Max Objective 2	20	184

Values for Objective2 are subtracted from each other (184-160 = 24)

The value found is divided by the number of intervals we specify.

R=(Objective 2 Value if Objective 1 is not considered- Objective 2 Value if Objective 1 added as constraint to the model)/grid number

R=24/4=6

First, Objective 2 value is found by adding R to the best value of Objective 2 in the Payoff table.

Objective2 = (160 + 6) ≥166 is added as a constraint to find the value of Objective1.

Same way, each value of Objective 2 value is found and added to the model as constraint and Objective 1 is maximized.

Objective2 = (166+6) ≥172

Objective2 = (172+6) ≥178

Objective2 = (178+6) ≥184

Objective1 values are found, separately.

The Decision Maker makes the choice between the values found.

5. APPLICATION OF THE PROPOSED MODEL ON AN EXISTING REVERSE LOGISTICS FACILITY IN TURKEY

In this study, we implemented our model to a Reverse Logistics Facility in Turkey. We choose refrigerators as recycled product. Model constructed as multi-objective, satisfying both economic and environmental concerns. Parameters are collected from various sources. For the parameters that we cannot find exact values approximate values are used. To estimate the amount of waste refrigerators, we used the previous years' refrigerator sales number in Turkey.

The material content differs according to the type and volume of the refrigerator. Proposed model thought as multi model.

In Appendix A, average materials rate obtained from a refrigerator is given. Revenues of each material sold as scrap, 2017 scrap metal prices are used. For hazardous materials, disposal cost of each one is determined by the information that is gained from authorized disposal firms.

Distance matrix is generated by using distance of seven regions from the existing RL facility. For fuel consumption of trucks, approximate prices are used.

Assumptions:

1. If a decision is made to collect from a region, the product can be collected in that year without paying an additional fee, other than transportation costs.
2. It is thought that there is no recruitment or dismissal in the given year
3. The manufacturer does not have to collect the products from every region; it is enough to reach the given goal.
4. It is assumed that there is no capacity limit for inventory.
5. The collected refrigerators are directly transferred to the RL facility.
6. The demand of the secondary market is unlimited.
7. The disposal cost paid for harmful products includes the cost of transporting those products.
8. Model is constructed as multi-product.

9. The amount of the material obtained from the recycling of the product is directly proportional to the weight of the product.
10. Machine process times are deterministic.
11. Recycle facility location is already determined.
12. The fee paid for new machines has been neglected.

This model answers the following questions:

1. How much is the company's net gain when it reaches the target collection numbers or how much does it cost if it has loss?

2. How much of the harmful wastes that are very important for the environment to be disposed properly are sent to the licensed firms?

3. In which period, from which region, how much product will be collected?

4. When does capacity increase needed?

5. What are the inventory levels and required labor sources?

5.1 Proposed Model and Description

Indices:

i: $Product\ index\ (i\ \in I)$

b: $Geographical\ regions\ \ index\ (b \in B)(b = 1, .., 7)$

t: $Periods\ (Months)\ (t \in T)(t = 1, .., 12)$

j: Material to be recovered from the products or disposed $(\mathrm{j} \in \mathrm{J})(\mathrm{j} = 1, \ldots, 9)$

m: Machine index $(m \in M)(m = 1, ..6)$

S: $Hazardous\ materials\ )(S \in J)(j = 7,8)$

Decision Variables:

$$Y_b = \begin{Bmatrix} 1, & if\ any\ product\ is\ collected\ from\ region\ b \\ & 0, \quad otherwise \end{Bmatrix}$$

x_{itb}: $Number\ of\ from\ product - i\ collected\ \ from\ region - b, in\ period\ t$

L_t: $Labor\ source\ that\ is\ required\ in\ period\ t\ (man * hour)$

I_{it}: $Inventory\ of\ product - i\ that\ is\ held\ at\ the\ end\ of\ period\ t$

Parameters:

LC_t: $Labor\ cost\ for\ per\ period\ in\ period\ t$

$F_b: Fixed\ cost\ of\ working$

$/aggreeing\ with\ a\ 3rd\ party\ provider\ to\ collect\ end\ of\ life$

$products\ from\ region\ b.$

$T_{im}: Time\ required\ to\ process\ the\ product\ i\ in\ machine\ m$

$G_i: Manual\ operational\ time\ per\ one\ piece\ of\ product - i.$

$Cap_{m,t}: Capacity\ of\ machine\ m\ in\ period\ t\ (hour)$

$H_i: Unit\ Inventory\ Holding\ cost\ of\ product\ i\ for\ one\ piece\ of\ product$

$per\ month\ \left(\frac{TL}{pieces * month}\right)$

$Dis_b = Distance\ of\ region\ b\ from\ the\ facility$

$R_j: Revenue\ that\ is\ gained\ from\ material\ j\ per\ kg$

$d_{itb} = amount\ of\ product\ i\ that\ can\ be\ recovered\ in\ period\ t\ from\ region\ b$

$TC: Unit\ transportation\ cost\ per\ km\ for\ one\ full - truck\ load.$

Mij: Material − j obtained out of one piece of product − i

$Cm: Cost\ of\ processing\ for\ one\ machine - m\ per\ hour.$

$weight_i = Weight\ of\ product\ type\ i$

Scalars:

$FTL: Full\ truck - load$

$Legcoproduction: Targeted\ collection\ amount$

$TC: Transportation\ cost\ per\ km$

$FCT: Fixed\ cost\ of\ a\ truck$

$FiCost: Annually\ fixed\ cost\ of\ the\ facility(maintanance, office, management..)$

Objectives :

Objective 1 (Cost minimization)

$$\begin{aligned} minz = & \sum_{t} L_t LC_t + \sum_{b \in B} F_b * Y_b + \sum_{b \in B} \sum_{t \in T} \sum_{i \in I} \frac{x_{itb}}{FTL} * TC * Dis_b * weight_i \\ & + \sum_{b \in B} \sum_{t \in T} \sum_{i \in I} \frac{x_{itb}}{FTL} * weight_i * \mathrm{FCT} + \sum_{b \in B} \sum_{t \in T} \sum_{i \in I} \sum_{m \in M} x_{itb} * T_{im} C_m \\ & + \sum_{i} \sum_{t} H_i I_{i,t} + - \sum_{j \in J} \sum_{i} \sum_{t} \sum_{b} (R_j) M_{ij} x_{itb} + FiCost \end{aligned} \tag{5.1}$$

Objective 2 (Recovery of most hazardous materials must be maximized)

$$\max z = \sum_{j \in S} \sum_{i} \sum_{t} \sum_{b} x_{itb} * M_{ij} \tag{5.2}$$

<u>Constraints:</u>

Capacity of machines

$$\sum_{i} \sum_{b} x_{itb} * T_{im} \leq Cap_{m,t};\ \forall t, \forall m \tag{5.3}$$

Legislation target constraint

$$\sum_{b} \sum_{t} x_{itb} \geq P_t \times legislation\ \ coefficient; (\forall i \in I) \tag{5.4}$$

Collection constraint

$$\sum_{b} \sum_{t} x_{itb} \leq \sum_{t} d_{itb}\,; (\forall i \in I) \tag{5.5}$$

Stock balance constraint

$$\sum_{i \in I} I_{i(t-1)} + \sum_{i \in I} \sum_{b \in B} x_{i(t+1)b} - \sum_{i \in I} \sum_{b \in B} x_{itb} = \sum_{i \in I} I_{it}\,;\ \ \forall (t > 1) \in T \tag{5.6}$$

Labor constraints

$$\sum_{i \in I} \sum_{b \in B} x_{itb} G_i \leq L_t\,; (\forall t \in T) \tag{5.7}$$

$$x_{itb} \in Z^{+};\quad \forall i \in I;\ \forall t \in T\,; \forall b \in B \tag{5.8}$$

$$L_t \geq 0;\ \forall t \in T \tag{5.9}$$

$$I_{i,t} \geq 0 \forall i \in I; \forall t \in T \tag{5.10}$$

$$Y_b \in \{0, 1\};\ \forall b \in B \tag{5.11}$$

In equation 5.1, in the first objective function, total cost is minimized. Labor source cost, installation cost of collection of used products system in given region, logistics cost (transportation and fixed cost of a truck for every tour), working machine cost ,total holding cost, annual fixed cost of facility and disposal cost of hazardous waste are cost parameters. Revenue gained from the recycled materials that is sold as scrap is substracted from the sum of them to find total cost.

In the equation 5.2 amount of materials that is properly disposed is maximized. Since not all of the materials are hazardous, only the most dangerous ones taken into account.

Equation 5.3 satisfies that required machine hour is no more than capacity of the machine. In equation 5.4 at least target amount of product is recycled that is set by legislations. Equation 5.5 ensures that maximum amount that can be collected from a region is available amount of product in that region. Available amount is equals to EEE that comes to end-of-life, so producer can collect them. The amount of recycled product cannot be more than the product that can be collected.

In stock balance constraint, equation 5.6, inventory of period equals to previous period's inventory plus next period's collection amount minus this period's collection amount.

In the equation 5.7 which is a labor constraint, required manual operation time equals to available labor source in man*hour.

Equations 5.8, 5.9 and 5.10 are non-negativity and integer constraints, x_{itb} amount of the collected product is integer and L_t and $I_{i,t}$ are greater than or equal to zero.

It is shown that Y_b(whether to collect from a region) is binary variable in equation (5.11).

5.2 Application of the Proposed Model

In this study, we implemented our model to a Reverse Logistics Facility in Turkey. Here in this section, results will be written after implementation of the proposed model by using GAMS. We chose refrigerator as product to be recycled. In reverse logistics, more than one objective may have targeted. Model constructed as multi-objective, satisfying both economic and environmental concerns. Here we want to show our models applicability with real world data set. First, model parameters will be described and then assumptions are explained.

Parameters are collected from various sources. Most parameters are collected from a refrigerator recycling facility in Eskisehir; others are gathered from online sources, previous studies. For the parameters that we cannot find exact values, approximate values are used according to available data.

5.2.1 Waste refrigerator amount estimation

Waste number is uncertain, so it should be estimated. At the same time, cost and other objective functions should have examined and trade-off between them should have analyzed. Waste estimation techniques in Widmer et al. (2005)'s study as follows:

1. In **Consumption and Use Method**, one type of electrical electronic equipment is selected and its number is used to predict WEEE. It requires data on the current stock assessment and average lifespan. This method may be useful in countries where little data available and WEEE inventory is not exist. In such a case, the method may provide a rough estimate with minimum data requirements (Ikhlayel, 2016). This method is based on the number of appliances owned households (stock in use) divided by the average lifetime of the appliance (Petridis et al, 2016). The formulation is like in equation (5.12);

   Where $H(t)$ number of product, $N_h(t)$ saturation level for per product and W is average weight and L is the average lifespan of the product.

   The European Environment Agency used this method to inspect waste from refrigerator, television and PCs in some countries.

$$WEEE_w(t) = \frac{H(t)N_h(t)W}{L}$$

(5.12)

2. **Market Supply Method,** uses data about production and sales figures in a given geographical region. According to this method, the total amount of electronic product sales in one particular year becomes waste when their average lifespan ends. (Petridis et al,2016). Improved version of this method is the 'market supply A' method, which assumes that lifespan of electronic equipment follows a statistical distribution. Matthews et al (1997)'s this model based on sales data and applicable only in USA. They select the PC's to analyze for their study and characterize them as first usage, second usage and store.
3. The **Time Step method** assumes, WEEE equals sales minus the difference between stock inflow and outflow where S (t) is the sales, and St (t) is the current stock quantities in a year t as shown in equation (5.13) and (5.14). It estimates WEEE based on sales and stock data.

$$WEEE_w(t) = S(t) - \{St(t) - S(t-1)\}$$

(5.13)

$$S(t) = I(t) + P(t) - E(t)$$

(5.14)

I (t) is the import quantities, P (t) is the production quantities and E(t) is the export quantities at evaluation year t.

4. **Swiss Environmental Agency's Estimation method** assumes that market of household is saturated and each appliance bought means one of them came to end-of-life
5. In the **Simple Delay method**, the WEEE generation in a year t is equal to historical sales data in a t−L year like in equation (5.15).

$$WEEE_w(t) = S(t-L)$$

(5.15)

6. **Mass balance method**: The advantage of applying the method is that it examines different EEEs paths (considering the number of sales, number of reused and the

number of stored), and it requires assumptions. Compared to other methods, more information about the fate of an EEE is required.

It gives accurate estimation ,where S(t−L) is the sold quantities $R(t-L_r)$ is the reused quantity S_r (t−L) is the stored quantity, L_r is the average lifespan of reused as shown in equation (5.16).

$$WEEE_w(t) = S(t-L) + R(t-L_r) + Sr(t-L_s) \tag{5.16}$$

It is proposed that a combination of methods may be employed to have an effective estimate of e-waste (Yedla, 2009).In Figure 5.1 all waste estimation techniques are summarized.

Method	Calculation	Required data			Applicable to		Accuracy
		Sales	Stock*	Lifespan	Saturated markets	Dynamic markets	
Distribution delay	Sales in previous years and distribution of lifespan	x		x	x	x	High
Sales	Sales at t	x			x		Low
Simple delay	Sales at (t – lifespan)	x		x	x		Medium
Time step	Stock at (t – 1) – Stock at t + (Sales – WEEE) until t	x	x		x	x	High
Carnegie Mellon	Includes data on behaviour of end user (hibernation/reuse/disposal)	x		x	x	(x)	High
Batch leaching (Stock & lifespan)	Stock at t/lifespan (or other parameter α)		x	x	x		Low
Econometric analysis	Depending on GDP or other parameters						Low

Figure 5.1: Waste estimation techniques summary table. (Polák& Drápalová, 2012)

In a completely saturated market with stable population, the quantity of new products sales equals e-waste output at the same time, which is named as the ‘‘Complete Saturation Method’’ (Walk, 2004).

To estimate the amount of waste refrigerator we use production and domestic sales data of Turkey. We have the previous years (1992 to 2015) production and domestic sales data of refrigerator semi-annually. We need the next years’ production and sales amount .With forecasting, next years’ refrigerator amount are estimated. Average lifetime of a refrigerator is accepted as 11 years.

The generation of e-waste from end of life products:

E-waste generation (weight or number) in the financial year ‘x -y’ = Sales in the financial year ‘(x-z) - (y-z)’where, ‘x–y’ = financial year in which generation is estimated, and z= average life span of EEE.

For example;

Estimated average lifetime of a refrigerator is z=11 years.

The estimation generation of end of life of refrigerator in 2016-17 is calculated as;

= Refrigerator Sales in the (FY year 2016-11 – 2017-11) either in terms of weight or number

= Sales in the financial year 2005-2006.

According to the data obtained from the White Goods Industrialists' Association (TÜRKBESD), annual production and sales ratios between 1992-2023 are given in APPENDIX A. Domestic sales and production rates and % changes has been taken from the report of İş Bankası for the years after 2009-2010. For the missing years, 2001 and 2009 missing point value estimation is applied. The years between 2017 and 2023 are obtained with forecasting methods.

Monthly sales and expected return amount of total product amount is given in APPENDIX A too. Simple delay method is used to find expected return amount. When determining the targets, since the type of products sold is not considered, the targets are given in total. In every year, first six months sales number is assumed the same, so do last six.

Demand amounts are given monthly for both Type1 and Type-2 for every region. For the first three regions, it is assumed that the coefficient number of products that comes to end-of-life is 2 and the other four regions’ are 1.

5.2.2 Material composition of the refrigerators and recovery rates

Every year approximately 3 million fridges bought and 3 million are disposed of in the UK. It is assumed to average lifetime of a refrigerator is 11 years, however, most of them are used for more than 20 years (Url-2).

Today refrigerators consist of several basic components; the cabinet and the door are made of aluminum or steel sheet metal. Inner cabinet is made of sheet metal, like the outer cabinet, or of plastic. Refrigerators are made of 60% metal and the majority comes from iron and steel. In fact, according to estimates made by the Device Recycling Institute, the average refrigerator contains 55 kg of steel (Url-4). The fins and pipes in the refrigerator are usually made from aluminum, copper or metal alloys and provide high-level heat conductivity. Copper is used for tubing due to its ductile structure and offer a high degree of thermal conductivity. Isolation between inner and outer cabinet is provided by fiberglass or polyurethane foam. Other inner parts made from vacuum-formed plastic and small parts like egg trays are also plastic (Url-4).

A refrigerator is based on two basic laws of physics; one that heat flows from warmer material to cooler materials and never do the reverse; two that decreasing the pressure of a gas also decreases its temperature (Url-6). Basic demonstrations of the parts are shown in Figure 5.2. Fan blades within the evaporator can be made of plastic, aluminum or steel. Compressor, which is a cooling part, is made of aluminum, copper, or alloy. Compressor is used to compress the refrigerant gas (R600a or R134). Capacitor limits the phase shift current/voltage when compressor is starting. Oil is used for lubrication of moving parts; however, gas is used for pumping the heat. Most fridges made before 2000 contain Chlorofluorocarbons (‘CFCs’) or Hydro chlorofluorocarbons (‘HCFCs’) in their insulation material and their refrigerant. CFCs and HCFCs are ozone-depleting substances (ODS), cause ozone layer destruction. Since 2010 ozone-friendly hydro fluorocarbon (HFC) refrigerants has begun to use. These refrigerants, however, still need to be carefully disposed since it spread greenhouse gases (Url-6). Household appliances may also contain hazardous components, including used oil, polychlorinated biphenyls (PCBs) and mercury.

In our study, we will examine a refrigerator recycling facility. Mechanical recycling of a refrigerator is as follows after arriving the facility (Figure 5.3):

1. Classification & Measurement of sizes and weight.
2. Manual Dismantling, Sorting and Separation:

Fridges emptied of any food, liquids, trays and shelves contained within. Hazardous substances should extract before the recycling.

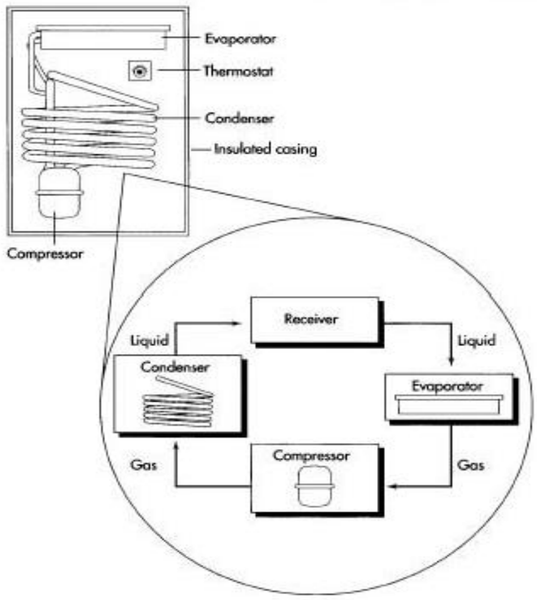

Figure 5.2: Parts of the refrigerator (Url-7)

A fridge/freezer contains ozone-depleting substances, such as CFC's. For fridge compressor where oil and coolant are found, oil is separated as reusable but coolant is separated for disposal.

- Cables, glass, mercury switches (if exits) are separated.
- Compressor is removed.
- Refrigerants gasses and oil are extracted

3. Shredding (Pre-shredding and Post-shredding):

   Refrigerators are fed into roller conveyors. Shredder makes fridge small manageable pieces by industrial shredder.

   Pre-shredding: The fridges are shredded in an enclosed nitrogen atmosphere and CFC gases in the insulating foam are released (Ur1).

   Post-shredding: The shredded contents are dried; the CFCs and nitrogen are captured and carried off for separating.

4. Pneumatic separation:
   Materials are finely sieved and heated to release. Sieving technique is used to extract the PUR foam from the other materials. The typical size of the foam particles is less than 2 mm. Shredding and sieving are completed within nitrogen atmosphere, providing a safe processing environment.

5. Ferrous metal separation:

Shredded materials pass under an electro magnet, ferrous metals are separated by this magnet for reuse or sell as scrap material. These materials are collected in large storage containers

6. Non-ferrous metal separation (aluminum, copper etc.):

From the remaining materials, non-ferrous metal is separated from the plastics for recycling by an eddy-current separator (Url-8).

7. Polyurethane separation (Pur-seperator) and pelleting
8. Plastic fraction

The non-ferrous materials are stored in a container and plastics are stored in large bags.

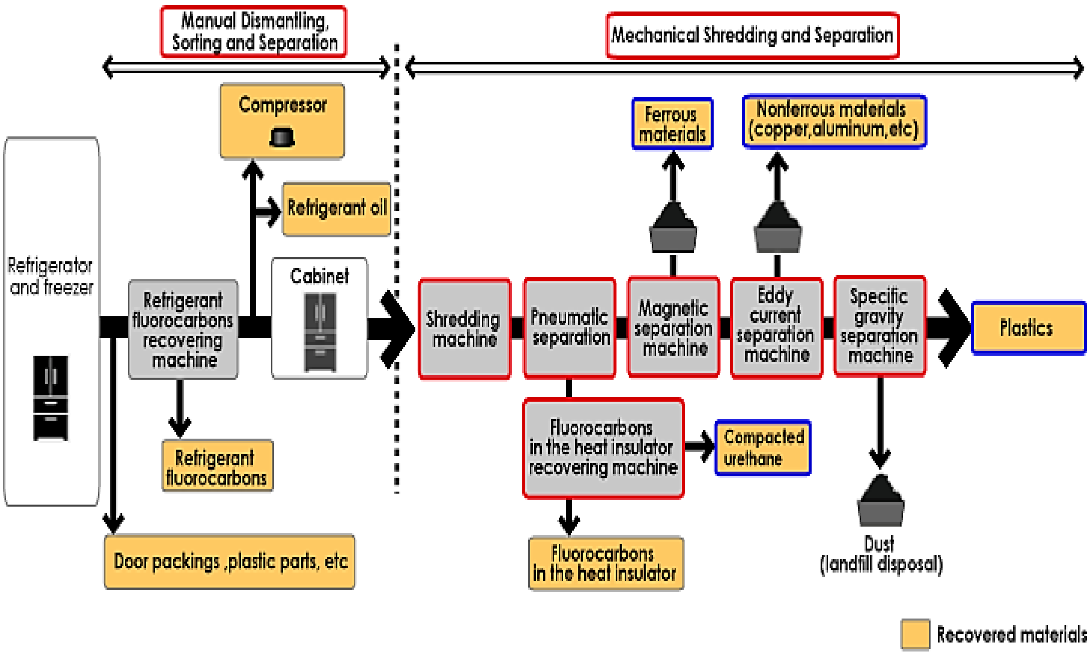

Figure 5.3: Refrigerator recycling steps (Url-1)

It is very important to determine the parameters so that the model to be installed can give accurate results. Every white-good product made from different materials. The material composition of the refrigerator is given in Figure 5.5. The revenue obtained for each material is gathered from 2017 current scrap price list. For hazardous materials, disposal cost of each one is determined by the information that is gained from authorized disposal firms. The scrap prices given are the average prices of the main factories purchasing 100 - 200 tons at one time (Url-5).

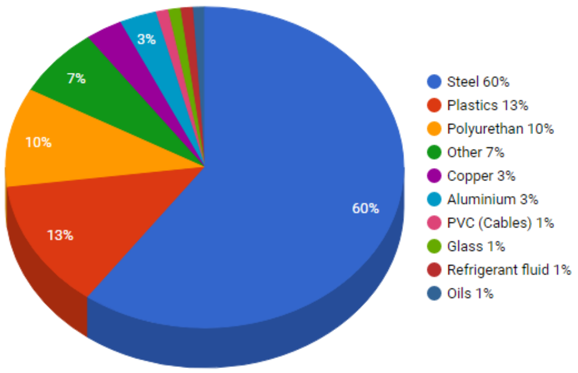

Figure 5.4: Obtained material rate after a refrigerator is recycled

It is assumed that there are two types of refrigerator in the multi-product model, and it is known that the facility is specialized only for the recycling of the refrigerator (Figure 5.6).

Scrap revenues from these materials and disposal costs of the hazardous ones are shown in Table 5.1.

Of the ten refrigerators sold, nine are Type-1, one is Type-2.

First refrigerator type is an average refrigerator used in the houses and the dimensions are as follows;

Height: 187, 5 cm Length: 80, 4 cm Width: 61, 5 cm Weight: 210 kg

The other type, which is known as bar type and dimensions are as follows;

Height: 96 cm Length54, 3cm Width: 51, 5 cm Weight: 210 kg

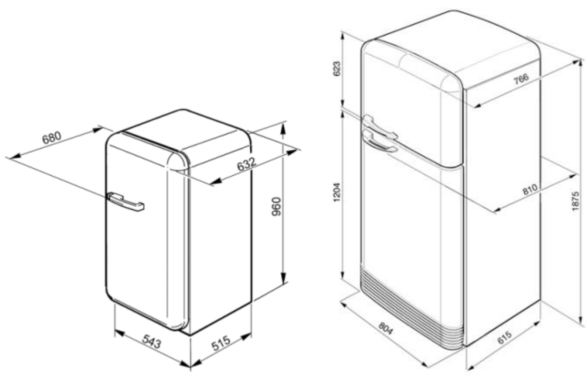

Figure 5.5: Bar-type refrigerator and single-door no frost refrigerator dimensions

Table 5.1: Material composition and scrap value prices for Type-1 and Type-2.

Material	Steel	Copper	Aluminum	Polyurethane	PVC (cable)	Glass	Refrigerant oil	Refrigerant gas	Plastic	Other
Composition ratio	60%	3%	3%	10%	1%	1%	1%	1%	13%	7%
Disposal cost of hazardous material	-	-	-	-	-	-	3.5	14	-	-
Price of scrap material per kg	0,5	15	4	1.1	5	0.4	-	-	1	0
Revenue obtained for product 1(30 kg)	15.3	16.2	2.7	3.3	1.5	0.12	-1.05	-4.2	3.9	0
Revenue obtained for product 2(110 kg)	56.2	59.5	9.9	12.1	5.5	0.45	-3.85	15.4	14.3	0

5.2.3 Calculating the collection targets

When calculating the quantities that a manufacturer of electric and electronic goods (EEE) will collect for a year, producers will perform collection operations taking into account the percentages targeted by the state. Targeted percentages are given in Table 5.1. For example, by multiplying the EEE sales in the relevant category in 2014 with the target percentage value for 2015, manufacturers will determine the amount of AEEE to collect. The amount of AEEE to be collected will be assessed in kg or ton. Here, targeted percentage of the returned ratio of refrigerators in Turkey between 2013 and 2030 is given in Table 5.1.

Table 5.2: Targeted percentage for the returned refrigerators in Turkey.

	2013	2014	2015	2016	2017	2018	2019	2020	2021
Freezer	1.25%	2.25%	4.25%	5%	5.50%	6%	6.5%	7%	10%
	2022	2023	2024	2025	2026	2027	2028	2029	2030
Freezer	12.5%	15%	17.5%	20%	22.5%	25%	30%	35%	40%

It will be decided whether to collect the products from 7 regions of Turkey. It is assumed that every region will collect products from its own cities and there is not an existing collection facility. Since the geographical position and industrial status of each region are different here, the cost of the plant for collecting the product is also determined in this direction and it differs from region to region.

5.2.4 Other model parameters

The plant has working hours of 420 minutes / shift, 2 shifts / day, 22 days / month. It is accepted that there are 12 periods in the model, which is established as multi-period, and each period is one month.

The provinces selected as collection centers were also determined in the same way considering both the geographical location and the industrialization rate. The distances of the selected provinces from the Eskisehir were taken as basis and distance matrix was created Table 5.3.Selected centers of every region is shown in Appendix A.

Table 5.3: Distance matrix.

Distance(km)	Marmara (1)	C. Anatolia (2)	Aegean (3)	Mediterr. (4)	Black Sea (5)	S. Anatolia (6)	E. Anatolia (7)
Eskisehir	155km	340 km	412 km	680 km	975 km	1030 km	1116 km

A truck with a length of 7.20 m, width of 2.45 m, height of 2.70 m and volume of 47 m^3 burns 25 liter of diesel per 100 km.

As a result of the agreements, the products emerging as the second product are taken by the scrap companies. Therefore, during the return of these products to the market, the company does not pay an extra transportation fee.

These harmful materials are completely removed from the product of the recycling plant and are destroyed in such a way as not to damage the environment in the specialized facilities for a certain price. Hazardous materials that are released must be transferred to licensed facilities. It is important to determine the transportation costs per kg for these materials, because in addition to the disposal fee, the cost of transporting the hazardous waste is also one of the cost elements. However, in our model we assume it is included in the disposal cost.

The holding cost of e-waste is determined by considering the volume it covers because there is no deterioration occurs in the short term. The holding cost of the refrigerator is also determined by taking capacity of the plant into account, because of the volume it covers is huge.

One of the main cost elements in the recycling plant is fixed costs. Manager, security, hardware and software, fixed energy and office costs are the main fixed costs. In our model, 500 000 TL is accepted as yearly fixed cost of the RL facility.

As the facility is already installed, no extra installation cost will be paid (land purchase, plant construction).

For each product, both manual and machine operations have to be done. Naturally, also in refrigerators, the processing time increases as the volume increases. In addition to the manual operations, the labor source is also required during the setting and monitoring of the machines.

In Table 5.5, Type-1 and in Table 5.6, the required operations for Type-2 refrigerator, the processing time and the capacities of the used machines are given. Since both types of refrigerators have the same operations, the required machine and capacity of machines are the same. The capacities of each machine are given in the same tables. Since it is known that each machine operates only one product at a time, the machine capacities are directly proportional to the operating time of the plant.

Table 5.4: Machine& labor requirements and machine costs for product Type-1.

Operation	Required Machine	Manuel work time required	Machine processing time	Capacity of the machine(minute) per period	Processing cost of the machine per hour
Classification and measurement	Manuel	1.5	-	-	-
Manual Dismantling, Sorting and Separation:	Manuel	5	-	-	-
Shredding	Shredder	0.5	4	19000	25
Pneumatic Separation	Magnetic Separator	0.5	1	19000	15
Ferrous metal Separation	Magnetic Separator	0.5	4	19000	15
Non-ferrous metal Separation	Eddy Current Separator	0.5	3	19000	15
Pur-separation	Pelletizer	0.5			10
Plastic fraction	Eddy Current Separator	0.5	2	19000	10
Total		9.5	17		

Table 5.5: Machine& labor requirements and machine costs for product Type-2.

Operation	Required Machine	Manuel work time required	Machine processing time	Capacity of the machine(minute) per period	Processing cost of the machine per hour
Classification and measurement	Manuel	0.8	-	-	-
Manual Dismantling, Sorting and Separation:	Manuel	2.5	-	-	-
Shredding	Two Shaft Shredder	0.25	1.8	19000	25
Pneumatic separation	Magnetic Separator	0.25	0.4	19000	15
Ferrous metal separation	Magnetic Separator	0.25	1.3	19000	15
Non-ferrous metal separation	Eddy Current Separator	0.25	1	19000	15
Pur-separation	Pelletizer	0.25	1		10
Plastic fraction	Eddy Current Separator	0.25	0.8	19000	10
Total		4.8	6.3		

Fixed cost of setting a collection system or dealing with third-party providers to do collection is different for every region as given in Figure 5.4. In our model, decision to whether to collect from the given region is made in every year.

Table 5.6: Fixed cost of collecting from region.

Price (TL)	Marmara (1)	C. Anatolia (2)	Aegean (3)	Mediterr. (4)	Black Sea (5)	S. Anatolia (6)	E. Anatolia (7)
Fixed cost of collecting from region	270000	230000	200000	180000	160000	140000	140000

5.3 Computational Results and Discussion

The purpose of this part is to show the computational results of the proposed mathematical model application to an existing RL facility that recycle refrigerators. The model has been solved in GAMS using CoinCbc and Clp Solvers, optimization software packages for solving mixed-integer linear programming problems.

All computational work was performed 64-bit operating system, Intel(R) Core™ i7-6500U 2.50 GHz CPU, and 8.00 GB RAM personnel computer. The model statistics are 267 single equation, 213 single variables, 2,412 non-zero elements, 7 discrete variables.

Between the years 2014-2018, two objective functions are tried to be optimized. Because they are overlapping functions, one gets better and the other gets worse. Between 2014-2018, the model is solved with AUGMECON, 5 different Pareto Optimal Solutions are obtained for each year. Since first objective function is important than second objective function, priority is given to first objective functions during calculations.

The target in the current AEEE directive is given in terms of the weight of the products sold at that time. However, it has been considered that the revised AEEE target is given in terms of the number of sold products. Therefore, both alternatives are tried separately and compared with each other.

5.3.1 When weight based target is given

<u>For 2014;</u>

We should calculate the best (ideal) and worst (nadir) values of objective functions over the feasible space and constructed Payoff Table as seen in Table 5.6.

Table 5.7: Payoff Table of 2014 for weight based target.

Payoff Table(2014)	Objective 1	Objective 2
Min Objective 1	827130	37458
Max Objective 2	1156723	188100

R= (188100-(37458))/4=37661

The range of the second objective function is divided into four equal intervals and resulting five grid points are found (Objective2 values). The value found is added to Objective 2 starting from the worst value found, respectively. The value found is added to the model as a constraint and corresponding Objective1 value is found. There are 5 different Pareto Optimal Solutions found which are shown in Table 5.8.

Table 5.8: Trade off table of 2014 for weight based target.

Trade offs	Objective 1 (TL)	Objective 2 (kg)	Y(b)>0	Labor source per month	Total collected WEEE in 2014
1	1156723	188100	1	752	57000
2	1079286	150440	1	752	45586
3	1001853	112779	1	752	34174
4	924420	75118,5	1	752	22761
5	827129	37458	3	752	11349

We see that the target quantity in 2014 is less than the amount of returned product, so we see only one type of product selected from a specific region. Type-1 product is selected because weight/required process time is more profitable than Type-2 product. The fact that only one tenth of the returning products are type 2 products and nine tenths are Type-1 products is a result of always collection of Type-1 products.

In Trade off-2, only Type-1 products are collected from the first region and collected product number is same in all periods except from 1 and 12. Average 752 hours per month labor source is required and since the distribution is constant in every month, there is no need to periodically labor fire and hire.

In Trade off-3, Type-1 products are collected from the first region. The number of products is the same except from 1 and 12 periods. These periods have slightly more collected products than the other periods (about one and half time), so there will be an imbalance in required labor source distribution.

In Trade off-5, third region has selected to collect the returned products. The cost of transportation is less important because it is decided to carry fewer products in this Trade off. That is why the cost of installing a new system is less expensive.

Only the first period, many products are collected, in the other periods less amount of product is collected.

In general, required labor sources are same in all Trade offs. Although the products collected are always Type-1, the decision on which regions to collect will vary. DM selects one of the Trade Offs according to priorities and criteria, makes decisions accordingly.

<u>For 2015;</u>

Payoff and Trade off tables for 2015 are shown in Figure5.9 and Figure 5.10.

Table 5.9: Payoff Table of 2015 for weight based target.

Payoff Table(2015)	Objective 1	Objective 2
Min Objective 1	982068	103156
Max Objective 2	1156723	188100

R= (103156-(188100))/4=21236

Table 5.10: Trade off table of 2015 for weight based target.

Trade offs	Objective 1 (TL)	Objective 2 (kg)	Y(b)>0	Labor source per month	Total collected WEEE in 2015
1	1156723	188100	1	752	57000
2	1113055	166864	1	752	54661
3	1069393	145628	1	752	44124
4	1025730	124392	1	752	39087
5	982068	103156	1	752	31250

In Trade off-1, only collected from the first product and the number of products collected in each period is the same. Therefore, the required labor source is constant and 753 hours. The target amount and available product for collection numbers are different from the previous one, but the number of remanufactured products is the same. We understand that the reason for this is the machine capacity limit. Even the returned products amount and target increases, machine capacities limit the recycled product amount.

For 2016;

Payoff and Trade off tables for 2016 are shown in Figure5.11 and Figure 5.12.

Table 5.11: Payoff Table of 2016 for weight based target.

Payoff Table(2016)	Objective 1	Objective 2
Min Objective 1	1355588	284837
Max Objective 2	1543446	376200

R= (376200-(284837))/4=22840,75

The capacity of the machines to recover the given targets is insufficient. Therefore, the number of machines 1, 3, 4 and 5 should be increased. Assuming that the number of machines is increased, the results are shown.

Table 5.12: Trade off table of 2016 for weight based target.

Trade offs	Objective 1 (TL)	Objective 2 (kg)	Y(b)>0	Labor source per month	Total collected WEEE in 2016
1	154346	376200	1	1500	114000
2	1496478	353359,25	1	1500	106960
3	1449512	330518,5	1	1500	100151
4	1402550	307677,75	1	1500	93228
5	1355588	284837	1	1500	86315

In Trade off-1, equal product amount is collected and processed. In all periods, 1500 labor hours required and 9500 Type-1 products are remanufactured in each period.

In all other trade off alternatives, the number of products processed in the first period is fixed and 9500, and the number of recycled products is reduced in the following months as the trade off goes to lowest cost.

For 2017;

Payoff and Trade off tables for 2017 are shown in Figure5.13 and Figure 5.14.

Table 5.13: Payoff Table of 2017 for weight based target.

Payoff Table(2017)	Objective 1	Objective 2
Min Objective 1	1448556	330053
Max Objective 2	1543446	376200

R= (330053-(376200))/4=11536,75

Table 5.14: Trade off table of 2017 for weight based target.

Trade offs	Objective 1 (TL)	Objective 2 (kg)	Y(b)>0	Labor source per month	Total collected WEEE in 2017
1	1543446	376200	1	1500	114000
2	1519722	364663,25	1	1500	109800
3	1496000	353126,5	1	1500	106900
4	1472272	341589,75	1	1500	103510
5	1448556	330053	1	1500	100056

In 2017, Trade Offs are seemed to be close alternatives since values are close to each other.

For 2018;

Payoff and Trade off tables for 2018 are shown in Figure5.15 and Figure 5.16.

Table 5.15: Payoff Table of 2018 for weight based target.

-

Payoff Table(2018)	Objective 1	Objective 2
Min Objective 1	1573116	390644
Max Objective 2	1801261	501600

R=(501600-(390644))/4=27739

It has been determined that the capacity is insufficient to reach the specified target.

The capacity of bottleneck operations should be increased. To do this, the number of 1, 3 and 6 machines should be increased.

Table 5.16: Trade off table of 2018 for weight based target.

Trade offs	Objective 1 (TL)	Objective 2 (kg)	Y(b)>0	Labor source per month	Total collected WEEE in 2018
1	1801261	501600	1	2006	152004
2	1744220	473861	1	2006	143592
3	1687183	446122	1	2006	135143
4	1630149	418383	1	2006	126780
5	1573117	390644	1	2006	118371

All products that are recycled are Type-1, meaning that it will be sufficient to collect only Type-1 products in zone 1 to achieve the intended collection goal. The decision made for the number of products will affect both the total cost and the amount of harmful waste recycled. The producers can determine one of these production plans on their own initiative.

5.3.2 When piece-based target is given

For 2014;

Payoff and Trade off tables for 2014 are shown in Figure5.17 and Figure 5.18.

Table 5.17: Payoff Table of 2014 for piece-based target.

Payoff Table(2014)	Objective 1	Objective 2
Min Objective 1	732832	22535
Max Objective 2	927789	188100

R=(22535-(188100))/4=41391,25

Table 5.18: Trade off table of 2014 for piece-based target.

Trade offs	Objective 1 (TL)	Objective 2 (kg)	Y(b)>0	Labor source per month	Total collected WEEE in 2014
1	927789	188100	1	820	99876
2	848052	146708,75	1	800	93377
3	808922	105317,5	1	788	65167
4	770212	63926,25	1	467	58705
5	732833	22535	3	325	25038

In the first four regions, both Type-1 and Type-2 are collected, however Type-2 is mostly preferred. For collection, only the 1st region is always preferred.

Unlikely, in Trade off-5, only Type-2 is collected. Required labor hour is also quite different between Trade offs. Required labor source is slightly less in Trade off-5.

<u>For 2015;</u>

Payoff and Trade off tables for 2015 are shown in Figure5.19 and Figure 5.20.

Table 5.19: Payoff Table of 2015 for piece-based target.

Payoff Table(2015)	Objective 1	Objective 2
Min Objective 1	754586	38642
Max Objective 2	927789	188100

R=(38642-(188100))/4=37364,5

In Trade off-4, Type-1 is collected only in the first 6 periods, Type-2 is in every period.In Trade off-5, only Type-2 is collected from Region 1.All trade offs in 2014 choose Region 1 to collect returned products.
As the number of collected products decreases, the required labor source decreases linearly. The labor source requirement is more homogeneous in the year than the weight-based target.

Table 5.20: Trade off table of 2015 for piece-based target.

Trade offs	Objective 1 (TL)	Objective 2 (kg)	Y(b)>0	Labor source per month	Total collected WEEE in 2015
1	927789	188100	1	830	84082
2	846067	150736	1	808	81135
3	806305	113371	1	756	76129
4	772231	76007	1	557	71559
5	754586	38642	1	600	79069

For 2016;

Payoff and Trade off tables for 2016 are shown in Figure5.21 and Figure 5.22.

Table 5.21: Payoff Table of 2016 for piece-based target.

Payoff Table(2015)	Objective 1	Objective 2
Min Objective 1	758455	71166
Max Objective 2	875813	164657

R= (71166-(164657))/4=23372,5

Table 5.22: Trade off table of 2016 for piece-based target.

Trade offs	Objective 1 (TL)	Objective 2 (kg)	Y(b)>0	Labor source per month	Total collected WEEE in 2016
1	875815	164657	1	830	79040
2	824024	141284	1	840	101000
3	788884	117912	1	830	978940
4	769835	94539	1	830	966441
5	758455	71166	1	590	790073

In trade off-1, usually same labor source are required for every period and both types of returned products are collected in each period.

In trade off-2, both types are collected and a similar labor source is required like trade off-1 in every period.

In trade off-3, periods between 1 to 6, both type of the products are collected however, Type-2 is collected in every period. Relatively higher labor source are required during the period when Type-1 products are being collected(with daily 5 hours and 115 hour per month labor source difference).

In trade off-4, only between the 2 to 6 periods Type-1 products are collected however, Type-2 products are collected in every period.In trade off-5, only from the Type-2 products are gathered and less labor sources are needed than other trade offs.

For 2017;

Payoff and Trade off tables for 2017 are shown in Figure5.23 and Figure 5.24.

Table 5.23: Payoff Table of 2017 for piece-based target.

Payoff Table(2017)	Objective 1	Objective 2
Min Objective 1	946203	119749
Max Objective 2	959368	130239

R= (119749-(130239))/4=2622,5

Table 5.24: Trade off table of 2017 for piece-based target.

Trade offs	Objective 1 (TL)	Objective 2 (kg)	Y(b)>0	Labor source per month	Total collected WEEE in 2017
1	1292330	130239	1	832	111391
2	1230987	127617	1,6	832	111392
3	1198727	124994	1,6	832	111392
4	1139876	122372	1,6	832	111990
5	1082348	119749	1,6	832	111990

For 2018;

Payoff and Trade off tables for 2018 are shown in Figure5.25 and Figure 5.26.

Table 5.25: Payoff Table of 2018 for piece-based target.

Payoff Table(2018)	Objective 1	Objective 2
Min Objective 1	1002153	123355
Max Objective 2	1012256	167640

R=(167640-(123355))/4=11071,25

In 2018, the number of bottlenecks for this year (machine 1) was increased to 2 machine.**Table 5.26:** Trade off table of 2018 for piece-based target.

Trade off's	Objective 1 (TL)	Objective 2 (kg)	Y(b)>0	Labor source per month	Total collected WEEE in 2017
1	1481091	167640	1,3	1045	139280
2	1397643	156568,75	1,6	1045	137202
3	1356783	145497,5	1,6	1045	137193
4	1309845	134426,25	1,3	1169	137121
5	1264341	123355	1,3	1169	137060

Comparison of two target type:

If the targets are given in units, products that are more advantageous will be preferred in terms of the value gained/unit. Other products may not be preferred because EEEs are usually collected which are either light in weight or more valuable when recycled.

In our model, bar type (Type-2) products are collected firstly if target is given in units. If the target is not reached, Type-1 refrigerators are being collected from the regions.

When the weight-based target is given, only the Type-1 product is collected because it is larger by weight and enough to reach the targets that are set by legislations.

5.4 Sensitivity Analysis for Scrap Prices and Disposal Cost

Sensitivity graphs shows the change in the scrap prices while the y-axis shows changes in Objective 1, x-axis shows alpha coefficient such as $\alpha = 0.8$, $\alpha = 0.9$, $\alpha = 1$, $\alpha = 1.1$, $\alpha= 1.2$.

For example, with multiplying α coefficient with normal value of steel scrap prices respectively, 5 different steel scrap value is obtained. With using these values, sensitivity analysis is conducted for cost minimization function.

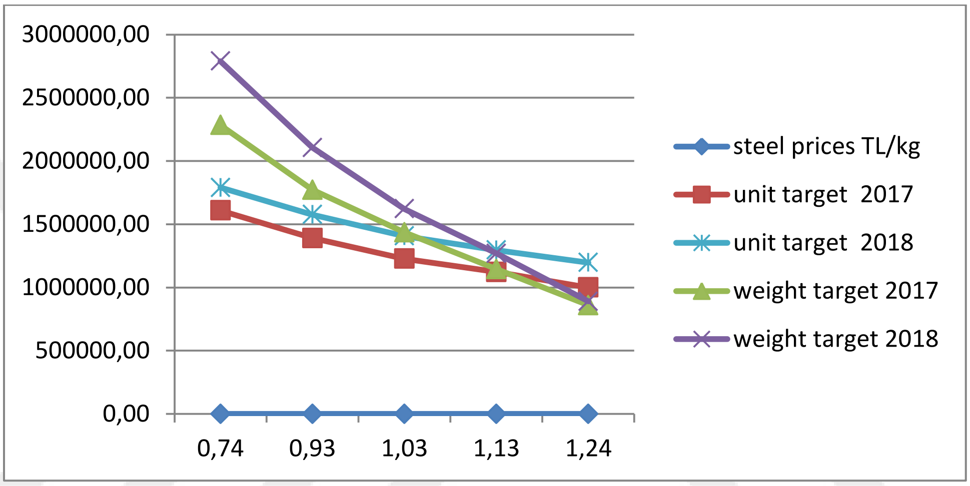

Figure 5.6: Sensitivity analysis of scrap prices of steel metal

There is no direct linear relationship between steel metal price and total cost. However, as the steel price increases, we can say that the cost decreases to a certain extent. If the target is given in units, it will cost less in all trials.

However, in total the lighter product is collected and recycled. In this case, less harmful material is properly disposed too. The cost decreases with the increase in scrap metal prices. Even though it decreases for both types of targets, if the target is set on weight based, the reduction will be sharper. If there is a 20% increase in the current price, the costs will be close for two target types. Moreover, if the steel price increases by more than 20 percent, the weight based target cost is less than the unit base target.

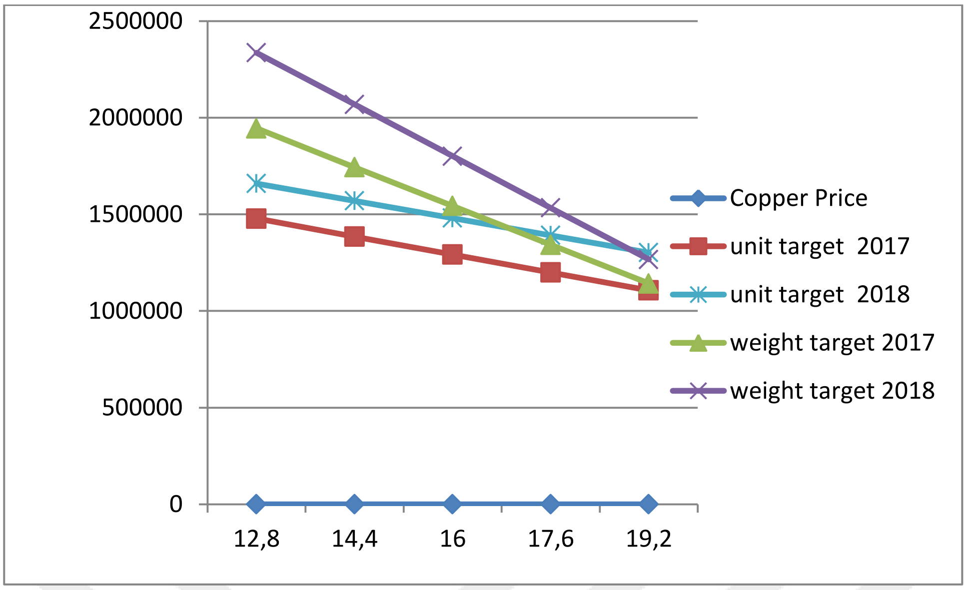

Figure 5.7: Sensitivity analysis of scrap prices of copper metal

Same procedure with α coeffcients is applied to copper scrap prices. In the case of the copper price change, the cost of the firm will also decrease as the income from the copper scrap rate is increased. The reduction is more linear. If the copper scrap purchase prices increase by 20%, the costs are equalized for the two target types.

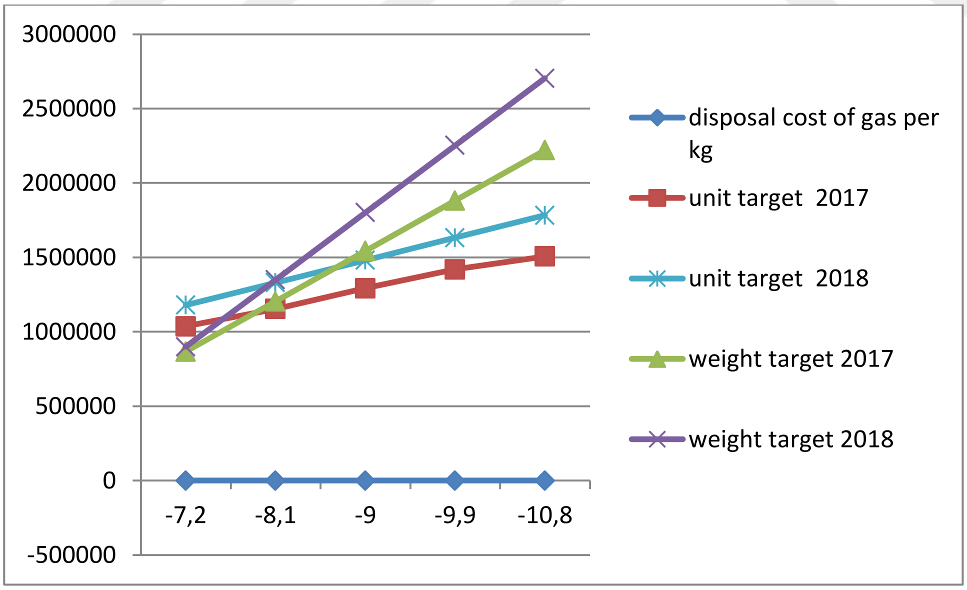

Figure 5.8: Sensitivity analysis of disposal cost of refrigerant gas.

As seen in the graph, the disposal cost of refrigerant gas is one of the basic units of cost.

The 20% reduction in the destruction of this harmful chemical can reduce the cost to almost zero. Producers have to send this harmful substance to the licensed company and + 20% change can double the cost.

RL activities for firms become much more favorable if the state supports the firm in the disposal of these harmful chemicals.Even small support to the firms for the disposal of these wastes can reduce the costs of firms' RL activities and even make them profitable.

6. CONCLUSION AND FUTURE RESEARCH

6.1 Conclusions

Reverse Logistics is a popular subject, which include all of the operations related with returned products collection, inspection and gaining value from them. First Reverse Logistics is mentioned and different perspectives of it examined in this study.

As an innovation in this study, two objectives, economic and environmental objectives were aimed at the same time. After the legal objectives are achieved, the economic objective (first objective) is accepted as more importantly, two objectives are tried to be optimized. In multi objective programming, if goals are contradictory, other goals are getting worse while one goal is getting better. In addition, when considering transportation costs, labor and energy requirements and plant costs, and an application in the industry and the results obtained, a different point of view emerged for the reverse logistics issue.

Because of the rapid increase WEEE amount, white-goods industry is selected for implementation. In addition, valuable materials that can be obtained from them show that economic and environmental values can be achieved from white goods if the right strategies are used.

The special cases in Turkey, driven forces of RL and handicaps of it are mentioned. As a driven force, with revision in the AEEE in Turkey, most of the firms forced to join RL activities because of penalties.

In this thesis, multi-objective model proposed to decide operations planning in an existing reverse logistics facility. In this deterministic MIP mathematical model, cost minimization and properly disposed hazardous material amount in terms of weight maximization has been targeted.

If the targets are given in units, they cost less for the companies. The recycled products are preferred from those that are lighter in weight or easier to carry. Piece-based target model is less affected by the scrap value changes and fuel prices fluctuations. However, recycled materials and properly disposed hazardous materials are comparatively less when this type target is set by government.

If targets are given in weight, firms prefer products heavy products. If the value of the scrap increases, a sharper decrease in cost is seen.

Therefore, it is important to set the target according to the product type.

For every situation we run, RL is an additional cost for the company. The company has not made any profit at all. As the years have passed and the target has increased, there has also been an increase in cost. In order to prevent this, the state may open its own facilities for the hazardous waste materials to be disposed of. As seen in the sensitivity analysis; the change in disposal cost is causing serious changes in cost. This support can make RL attractive for companies.

In order to increase the number of products collected, incentive may be given per person to give their used products. However, this is a burden for the companies. If the state imposes a legal sanction to prevent these wastes from being discarded, people will have to leave these wastes to the competent authorities.

6.2 Recommendations for Future Research Works

Nature of the supply chain is uncertain; when it comes to reverse supply chain, it comprehends more uncertainty than traditional supply chain because of its’ more dynamic nature. Parameters that are assumed uncertain previous studies are demand, amount of returned products, costs and scrap prices that are considered in some papers. However, some parameters should also evaluate as uncertain; delivery time, lead-time, transportation time, waste generation, environmental issues, risk factors and different weights. In our study, sensitivity analyses have conducted with scrap prices and disposal cost of refrigerant gas. Other parameters can be analyzed with stochastic programming.

Stochastic modeling is more developed area since it gives accurate results in OR however requirements of historical data and complexity of modeling making it impractical. If more accurate historical data are available for the returned product quantity and the returned product quality, the model is installed more accurately and results that are more realistic are obtained.

In our study, only the refrigerator recycling was examined and the model was set up and operated on the targets given for large household appliances. As it can be applied to other electronic devices, the scope of the work can be extended even to the automotive sector.

From the beginning of the production, selecting materials and assembling them so that disassembly can be done easily and parts can be reused can also make the process easier by lowering RL costs.

An increase in capacity may require an additional processing plant when the targets increase. Establishment of the second plant in the other regions of the country would be very beneficial with reducing transport costs and contributing to industrialization and employment in that region.

As the targets grow, the number of products that need to be collected will increase. In order to reach the targets, it is necessary to investigate whether consciousness of the public is sufficient or incentive should be given to collect enough used products.

Scrap values are sensitive parameters for the RL model we are installing. For this reason, parameter estimates should be done correctly in the coming years in order to make cost calculations correctly.

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APPENDICES

APPENDIX A: Model data

APPENDIX B: Model GAMS code

APPENDIX A

Table A.1: Production and domestic sales number of refrigerators in Turkey.

Year	Production	Domestic Sale	% Production change	%Sale change
1992	1087416	796715		
1993	1247016	927180	15	16
1994	1265135	767267	1	-17
1995	1620919	827338	28	8
1996	1638018	963374	1	16
1997	1849513	1230743	13	28
1998	1875089	1407844	1	14
1999	2139259	1257749	14	-11
2000	2446000	1468000	14	17
2001	2482004	1501499	1	2
2002	3318000	1088000	36	-26
2003	4286000	1362000	29	25
2004	5308000	1991000	24	46
2005	5538000	1961000	4	-2
2006	6740000	2110000	22	8
2007	6865000	1940000	2	-8
2008	6002000	1907000	-13	-2
2009	6724590	2080263	12	9
2010	6311000	1676000	5	-12
2011	6790000	1900000	8	13
2012	7589000	1879000	12	-1
2013	7226000	2003000	-5	7
2014	6659000	1908000	-8	-5
2015	6833000	1976000	3	4
2016	8320618	2227978	22	13
2017	8638676	2284338	4	3
2018	8956735	2340699	4	2
2019	9274793	2397060	4	2
2020	9592851	2453421	3	2
2021	9910910	2509782	3	2
2022	10228968	2566142	3	2
2023	10547026	2622503	3	2

Table A.2: Monthly sales and expected returns semi-annually for both Type1 and Type2.

Month s-year	Monthly sales	Sales	Target	Year-S	Expected Return		Targeted recycle amount(unit)	Targeted recycle amount(weight(kg))
					Type1	Type2		
1*6 months 13	131243	2003000	0,0125	2002-1	1087104	120789	25038	2553825
2*6 months 13	169737			2002-2	1370880	152320		
1*6 months 14	139934	1908000	0,0225	2003-1	1360879	151209	45068	4596885
2*6 months 14	180616			2003-2	1716120	190680		
1*6 months 15	148624	1976000	0,0400	2004-1	1989361	221040	79640	8123280
2*6 months 15	191496			2004-2	2508660	278740		
1*6 months 16	157315	2227978	0,0500	2005-1	1959386	217710	98800	10077600
2*6 months 16	202375			2005-2	2470860	274540		
1*6 months 17	166005	2284338	0,0600	2006-1	2108263	234251	133679	13635225
2*6 months 17	213254			2006-2	2658600	295400		
1*6 months 18	174696	2340699	0,0600	2007-1	1938403	215378	137060	13980148
2*6 months 18	224133			2007-2	2444400	271600		
1*6 months 19	183386	2397060	0,0700	2008-1	1905430	211714	163849	16712590
2*6 months 19	235012			2008-2	2402820	266980		
1*6 months 20	192077	2453421	0,0700	2009-1	2078551	230950	167794	17115008
2*6 months 20	245891			2009-2	2621132	291237		
1*6 months 21	200767	2509782	0,1000	2010-1	1674620	186069	245342	25024894
2*6 months 21	256771			2010-2	2111760	234640		
1*6 months 22	209458	2566142	0,1300	2011-1	1898436	210937	326272	33279709
2*6 months 22	267650			2011-2	2394000	266000		
1*6 months 23	218148	2622503	0,1500	2012-1	1877453	208606	384921	39261972
2*6 months 23	278529			2012-2	2367540	263060		

Table A.3: Semi-annually demand for product Type-2 in 7 regions.

	Demand for Type 2(Returned Products)						
Month-Year	Region1	Region2	Region3	Region4	Region5	Region6	Region7
1*6 months 13	4026	4026	4026	2013	2013	2013	2013
2*6 months 13	5077	5077	5077	2539	2539	2539	2539
1*6 months 14	5040	5040	5040	2520	2520	2520	2520
2*6 months 14	6356	6356	6356	3178	3178	3178	3178
1*6 months 15	7368	7368	7368	3684	3684	3684	3684
2*6 months 15	9291	9291	9291	4646	4646	4646	4646
1*6 months 16	7257	7257	7257	3629	3629	3629	3629
2*6 months 16	9151	9151	9151	4576	4576	4576	4576
1*6 months 17	7808	7808	7808	3904	3904	3904	3904
2*6 months 17	9847	9847	9847	4923	4923	4923	4923
1*6 months 18	7179	7179	7179	3590	3590	3590	3590
2*6 months 18	9053	9053	9053	4527	4527	4527	4527
1*6 months 19	7057	7057	7057	3529	3529	3529	3529
2*6 months 19	8899	8899	8899	4450	4450	4450	4450
1*6 months 20	7698	7698	7698	3849	3849	3849	3849
2*6 months 20	9708	9708	9708	4854	4854	4854	4854
1*6 months 21	6202	6202	6202	3101	3101	3101	3101
2*6 months 21	7821	7821	7821	3911	3911	3911	3911
1*6 months 22	7031	7031	7031	3516	3516	3516	3516
2*6 months 22	8867	8867	8867	4433	4433	4433	4433
1*6 months 23	6954	6954	6954	3477	3477	3477	3477
2*6 months 23	8769	8769	8769	4384	4384	4384	4384

Table A.4: Semi-annually demand for product Type-1 in 7 regions.

	Demand for Type 1(Returned Products)						
Month-Year	Region1	Region2	Region3	Region4	Region5	Region6	Region7
1*6 months 13	36237	36237	36237	18118	18118	18118	18118
2*6 months 13	45696	45696	45696	22848	22848	22848	22848
1*6 months 14	45363	45363	45363	22681	22681	22681	22681
2*6 months 14	57204	57204	57204	28602	28602	28602	28602
1*6 months 15	66312	66312	66312	33156	33156	33156	33156
2*6 months 15	83622	83622	83622	41811	41811	41811	41811
1*6 months 16	65313	65313	65313	32656	32656	32656	32656
2*6 months 16	82362	82362	82362	41181	41181	41181	41181
1*6 months 17	70275	70275	70275	35138	35138	35138	35138
2*6 months 17	88620	88620	88620	44310	44310	44310	44310
1*6 months 18	64613	64613	64613	32307	32307	32307	32307
2*6 months 18	81480	81480	81480	40740	40740	40740	40740
1*6 months 19	63514	63514	63514	31757	31757	31757	31757
2*6 months 19	80094	80094	80094	40047	40047	40047	40047
1*6 months 20	69285	69285	69285	34643	34643	34643	34643
2*6 months 20	87371	87371	87371	43686	43686	43686	43686
1*6 months 21	55821	55821	55821	27910	27910	27910	27910
2*6 months 21	70392	70392	70392	35196	35196	35196	35196
1*6 months 22	63281	63281	63281	31641	31641	31641	31641
2*6 months 22	79800	79800	79800	39900	39900	39900	39900
1*6 months 23	62582	62582	62582	31291	31291	31291	31291
2*6 months 23	78918	78918	78918	39459	39459	39459	39459

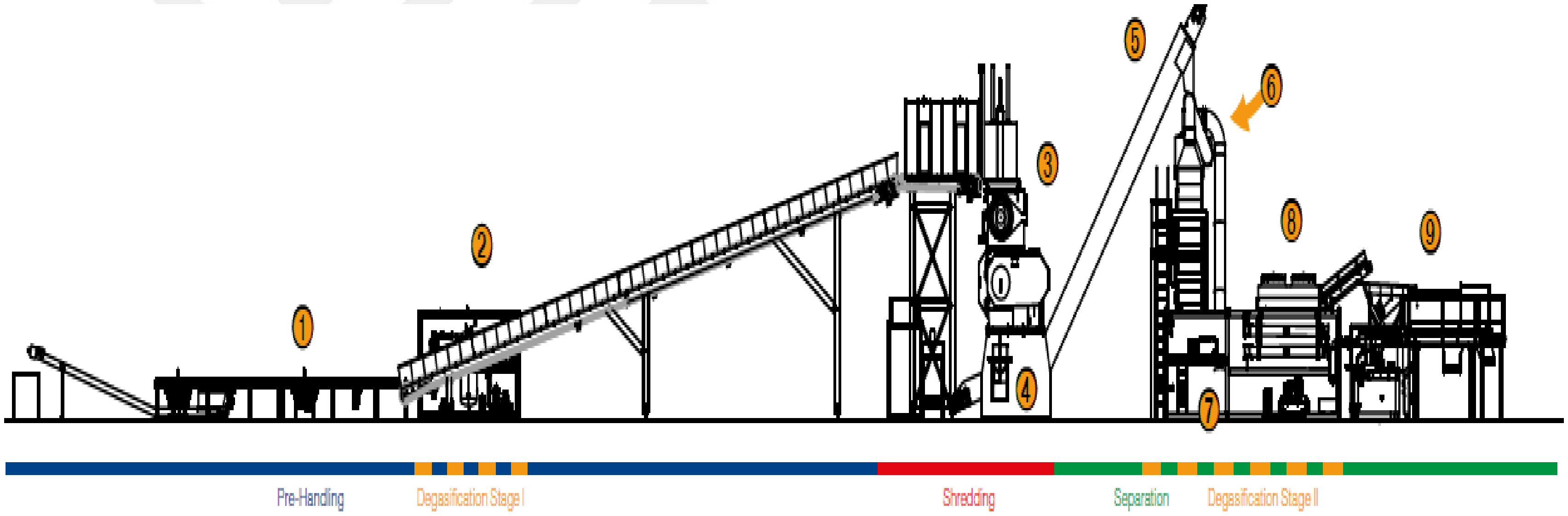

Figure A.1: Example refrigerator recycling machine system

APPENDIX B

Sets
i /   1*2/
* big,small/

j /1*9/
*   steel, copper, aluminum, polyurethan,pvccable, glass, refoil, refrigerantsgas, plastic/

b /1*7/
*   akdeniz, karadeniz, marmara, ege, doguanadolu, icanadolu,guneyd   /

t /1*12   /

m/1*6/
* Shredding,Pneumaticseperation,Ferrousmetalseperation ,   Non-ferrousmetalseperation, Pur-seperatorPolyurethaneseperation, Plasticfraction   / ;

Parameters

LC(t)/1*12 0.1/

F(b)/1 270000,2 230000,3 200000,4 180000,5 160000,6 140000,7 140000/

Time(i,m)/1.1 4, 1.2   1, 1.3 4, 1.4 3 , 1.5 3, 1.6 2,
2.1 1.8, 2.2 0.3, 2.3 1.3, 2.4 1, 2.5 1, 2.6 0.7 /

G(i)/1 9.5, 2 4.8/
*Gi: Manual operational time per one piece of product-i.

Cap(m,t)/
1.1*12 57000, 2.1*12 19000, 3.1*12 38000, 4.1*12 38000, 5.1*12 38000, 6.1*12 38000 /
*Cap(m,t):Capacity of machine m in period t (hour)

H(i)/1 1,2 0.4/
*H_i:Unit Inventory Holding cost of product i for one piece of product per month (TL/(pieces*month))

Dis(b)/1 155,
2 340,
3 412,
4 680,
5 975,
6 1030,
7 1116/

```
*D_b=Distance of region b from the facility

d(i,t,b)/1.1*6.1*3 65313     ,
1.7*12.1*3 82362        ,
1.1*6.4*7  35138   ,
1.7*12.4*7 35138     ,
2.1*6.1*3 7257     ,
2.7*12.1*3 9151,
2.1*6.4*7 362      ,
2.7*12.4*7 4576
        /


Mac(i,j)/
1.1 50,1.2 2.2,  1.3 3.3, 1.4 11, 1.5 1.1, 1.6 1.1, 1.7 1.65, 1.8 1.65, 1.9 11.7,
2.1 13,2.2 0.6, 2.3 0.9, 2.4 3, 2.5 0.3, 2.6 0.3, 2.7 0.45, 2.8 0.45, 2.9 2.4
/
*Mij: Material-j obtained out of one piece of product-i.

R(j)/1 0.5, 2 8, 3 2, 4 0.55, 5 0.25, 6 0.2, 7 -11.5, 8 -18,9 0.1 /
*R_j:Revenue that is gained from material j per kg

C(m)/1 0.42, 2 0.25, 3 0.25, 4 0.25 , 5 0.17, 6 0.17 /
*Cm: Cost of processing for one machine-m per minute.

weight(i )/   1 110,2 30/;

Binary Variables
Y(b);
*Y_b={?(1,if any product is collected from region b@0,    otherwise)}

integer Variables

x(i,t,b);
*x_itb: Number of from product-i collected   from region-b,in period t

Positive Variables

L(t)
*L_t:Labor source that is required in period t (man*hour)

Inv(i,t)
*I_it:Inventory of product-i that is held at the end of period t
*s2;

Variables
Objective1
Objective2;
```

```
Scalar
FTL/  8000/
*TC /250/
Legcoproduction   /  11001778 /

*epsilon/0.000001/
*r2/15561/;


Equations
obj1
obj2
capacityconst
stockbalance
laborconst
collcons
legislconst
amac    ;
obj1..Objective1=e=sum((t),L(t)*LC(t))+sum((b),F(b)*Y(b))+sum((b,t,i),x(i,t,b)*wei
ght(i)*Dis(b)*2.25/FTL)+sum((b,t,i),x(i,t,b)*weight(i)/FTL *500)
+sum((b,t,i,m),x(i,t,b)*Time(i,m)*C(m))+500000-sum((j,i,t,b),R(j)*Mac(i,j)*x(i,t,b))
+ sum((i,t),H(i)*Inv(i,t)) ;

obj2.. Objective2=e=-sum((i,t,b),x(i,t,b)*Mac(i,"7"))-sum((i,t,b),x(i,t,b)*Mac(i,"8"));

capacityconst(m,t).. sum((i,b),x(i,t,b)*Time(i,m))=l=Cap(m,t);
stockbalance(t)$(ord(t) gt 1)..sum((i,b),Inv(i,t-1)+x(i,t+1,b)-
(x(i,t,b)))=e=sum(i,(Inv(i,t)));
laborconst(t)..sum((i,b),x(i,t,b)*G(i))=e=L(t);
collcons(i,t,b)..x(i,t,b)=l=d(i,t,b)*Y(b);
legislconst..sum((i,t,b),x(i,t,b)*weight(i))=g=Legcoproduction ;
amac.. Objective2=l=-376200
;

Model model1  / all /;

solve model1 minimizing Objective1 using MIP    ;

*solve model1 minimizing Objective2 using MIP   ;

display x.L
display y.L
display L.L
display Inv.L
*display s2.L
display Objective1.L                        ;
display Objective2.L
```

CURRICULUM VITAE

PHOTO

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