A MULTI-CRITERIA REVERSE LOGISTICS NETWORK DESIGN FOR WASTE ELECTRICAL AND ELECTRONIC EQUIPMENTS

by

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to the one who cannot simply write a thesis

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A MULTI CRITERIA APPROACH FOR DESIGNING A NETWORK OF WASTE OF ELECTRICAL AND ELECTRONIC EQUIPMENT

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Abstract

The quantity of electrical and electronic equipments (EEEs) introduced in the market has been growing fast since EEEs have become an indispensable part of our daily life. The performances of the products are steadily increasing while their prices are decreasing. Moreover, the decreasing lifespan of EEEs and expanding range of the products directly affect the size of the EEE market. One consequence of this expansion is waste EEEs (WEEEs) occurring after the end of use or end of lifespan. WEEE contain various hazardous substances which may cause severe damage to the environment and various health related problems. Therefore, developing proper waste management strategies and operations is crucial. Many countries have implemented environmental legislations for WEEE management. In these regulations, the responsibilities of stakeholders, such as EEE producers, logistics service providers and municipalities, are specified clearly. Similarly, the Ministry of Environment and Urbanization in Turkey started implementing WEEE Directive in May 2012. Even though responsibilities of related authorities are stated in this directive, scrap dealers still collect and treat WEEEs illegally. These scrap dealers are not equipped with necessary tools and conditions for the suitable treatment of WEEEs, which creates risk for their own health and inefficiency in the system. For this reason, they might be included in WEEE management system by being supported by the government. This study proposes multi objective mixed integer linear programming model for handling of the WEEEs, based on the requirements set by Turkish WEEE Directive. In this study, the proposed model is designed for multi-echelon, multi-product, multi-period reverse logistics network and is solved by IBM ILOG CPLEX Optimization Software 12.6. The proposed model is validated by using the amount of WEEE to be collected in Istanbul, considering WEEE collection target per capita specified in the directive. The model has three objective functions reflecting the three pillars of sustainability. The first objective of this model is to maximize the profit of the overall WEEE management system when illegal scrap dealers are included. The second objective is to minimize the environmental impact while designing network. Third objective is to increase employment by incorporating illegal scrap dealers into WEEE management stream. Results of the study suggest opening WEEE treatment facilities in specified locations and subsidizing the scrap dealer junkyards which will be incorporated into WEEE management system. This study proves the importance of efficient WEEE management and provides a managerial insight for governmental authorities and professionals.

ATIK ELEKTRİKLİ VE ELEKTRONİK EŞYALAR İÇİN ÇOK KRİTERLİ TERİNE LOJİSTİK AĞ TASARIMI

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Özet

Elektrikli ve elektronik eşyalar (EEE) günlük hayatımızın vazgeçilmez bir parçası haline geldiğinden, piyasaya sunulan EEE miktarı hızla artmaktadır. Ürünlerin performansları düzenli olarak artarken fiyatlar da düşmektedir. Üstelik, EEE'lerin ömrünün azalması ve ürün çeşitliliğinin artması, EEE pazarının büyüklüğünü doğrudan etkilemektedir. Bu genişlemenin bir sonucu, kullanımı biten veya ömrü sona eren ürünlerin ortaya çıkardığı atık EEE'lerdir (AEEE). AEEE çevre ve insan sağlığı için tehlikeli maddeler içermektedir. Bu nedenle uygun atık yönetimi stratejileri ve prosedürleri geliştirmek çok önemlidir. Bir çok ülkede AEEE yönetimi için çevre yönetmelikleri yürürlüğe konmuştur. Bu düzenlemelerde, EEE üreticileri, lojistik hizmet sağlayıcıları ve belediyeler gibi paydaşların sorumlulukları açıkça belirtilmektedir. Benzer şekilde, Türkiye'de Çevre ve Şehircilik Bakanlığı, Mayıs 2012'de AEEE Yönetmeliği'ni uygulamaya başlamıştır. İlgili paydaşların sorumlulukları bu direktifte belirtilmiş olsa da, hurda satıcıları hala AEEE'leri yasadışı olarak toplamakta ve işlemektedir. Bahsi geçen hurdacılar AEEE'ları işleyebilmek için gerekli olan ekipman ve koşullara sahip olmadıklarından hem kendi sağlıklarını tehlikeye atmaktadırlar hem de atık sisteminin verimliliğini düşürmektedirler. Bu nedenle, devlet tarafından desteklenerek AEEE yönetim sistemine dahil edilebilirler. Bu çalışma, AEEE'lerin ele alınması için, AEEE Yönetmeliği'nin belirlediği şartlara göre, çok amaçlı karma tamsayılı doğrusal programlama modeli sunmaktadır. Bu çalışmada, önerilen model, çok aşamalı, çok ürünlü, çok dönemli tersine lojistik ağı için tasarlanmış ve IBM ILOG CPLEX Optimizasyon Yazılımı 12.6 ile çözülmüştür. Önerilen model, yönetmelikte belirtilen kişi başına düşen AEEE toplama hedefi dikkate

alınarak İstanbul'da toplanacak AEEE miktarları kullanılarak test edilmiştir. Modelin sürdürülebilirliğin üç dalını yansıtan üç ayrı amaç fonksiyonu vardır. Bu modelin ilk amacı, yasadışı hurda satıcıları dahil edildiğinde AEEE yönetim sisteminin kârını en büyüklemektir. İkinci amaç, tasarlanan ağın çevresel etkisini en küçüklemektir. Üçüncü amaç ise, yasadışı atık satıcılarını da AEEE yönetim akışına dahil ederek istihdamı en büyüklemektir. Çalışmanın sonuçları, belirtilen yerlerde AEEE ayrıştıma tesislerinin açılmasını ve AEEE yönetim sistemine dahil edilecek hurda satıcısı hurdalarının sübvanse edilmesini önermektedir. Bu çalışma verimli atık yönetiminin önemini vurgulamaktadır ve devlet yetkilileri ve profesyoneller için yol göstericidir.

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Chapter 1

Introduction

This thesis presents a reverse logistics network design model for waste electrical and electronic equipment generated in Istanbul. In this chapter, I will start with defining the problem and motivation behind this research. Further, I will provide an overview of the contributions of this thesis and then discuss its structure.

Electrical and Electronic Equipments (EEE) are an important part of everyday life inevitably. The number of EEE put on the market place is increasing in relation to the growing population and consumer needs. Moreover, consumer behavior is influenced by EEE with expanded functionalities with meanwhile decreasing prices. It is also crucial that EEE consumption rate is accelerated by the decreasing lifespans and increasing range of new product types [3]. This increasing expenditure rate for EEE causes accumulation of Waste Electrical and Electronic Equipment (WEEE) all around the world [4]. Beside the fact that WEEE is one of the fastest expanding waste streams, it requires proper waste management strategies due to various complicated hazardous substances included in WEEE which may result in loss of resources and substantial damage to the environment [5, 6]. Due to these toxic ingredients, consisting of heavy metals and harmful chemical such as lead, cadmium, mercury, arsenic etc., WEEE is classified as hazardous waste [7]. In addition to dangerous content, WEEE also still contains precious recoverable materials inside which provide profit opportunities for manufacturers, either as a valuable source of recyclable raw materials or with the re-use of components and their re-introduction to the manufacturer's supply chain [8]. For this reason, proper recovery operations for materials or components are highly crucial in a world with increasingly scarce natural resources.

Both limited natural resources and increasing waste issues are essential reasons behind the sustainable development idea which firms, societies and governments have increased their attention towards it in the past years. World Commission on Environment and Development (WCED) stated that 'sustainability is a development that meets the needs of the present without compromising the ability of future generations to meet their needs' [9]. In that manner, the structures of industrial economies should be changed so as to be using energy and resources efficiently, reducing the wastes, emissions and technologically dangerous effects [10]. Environmental regulations that have been imposed in various countries are evidence of the intention to preserve the world we live in. Some of these regulations are guidance for WEEE management and define certain responsibilities of the actors of the network that WEEE flows on, such as manufacturers, logistics service providers and municipalities. For instance, European Union (EU) Directives 2002/96/EC and 2002/95/EC are two of the most stringent regulations regarding WEEE (European Parliament and of the Council, Directive 2002/96/EC and 2002/95/EC 2002). Preventing WEEE, imposing recovery activities and developing the environmental performance of all actors in the chain are the fundamental objectives of the Directive [9].

Turkey implemented the directive of the European Parliament and of the Council of 27 January 2003 on Waste Electrical and Electronic Equipment ('WEEE Directive',2002/96/EC) by maintaining similar purposes to those mentioned above. The current directive divides almost all electrical and electronic equipment used by consumers or business into ten categories and sets recovery and recycling targets for each category [11].

To achieve the recovery and recycling rates indicated in the directives, it is mandatory to construct an effective network. Such a network system can be regarded as a strategic decision-making process which includes comprehensive designing and planning. The designing stage includes strategic (long-term) decision such as the locations and types of storage points, as well as of recycling facilities. Since these decisions have enormous influence on the total cost, this critical decision-making process should be handled systematically. In the planning stage, the most important decision variables are the quantities of flows between supply-chain network entities known as mid-term decision variables [2, 12].

In literature, there are many researchers who are fascinated by this comprehensive network design problem which is a subject of the field of Reverse Logistics. Two of them, De Brito and Dekker, define RL as following: "It is the process of planning, implementing and controlling backward flows of raw materials, in-process inventory, packaging and finished goods, from a manufacturing, distribution or use point, to a point of recovery or point of proper disposal". In this context, there are several Reverse Logistics Network Design (RLND) studies which are parallel to goals of current directives. For instance, Kılıç [2] designed a RLND model considering the recycling rate constraint which provides the minimum rates indicated in the WEEE Directive of Turkey. Another study is conducted by Lehtinen and Poikela [13]. This paper first defines the requirements of the legislation in Finland and continues with a discussion regarding the current situation of recycling management in the country by comparing with WEEE directive.

In addition to researchers, RL activities attract the attention of business professionals. Increase in environmental awareness among societies and legislations for recycling have been putting pressure on many manufacturers and consumers, forcing them to produce and dispose of products in an environmentally responsible manner [14]. Moreover, RL will be more crucial in term of service management activities and take-back for products such as automobiles, refrigerators and other white goods, cellular handsets, lead-acid batteries, televisions, personal computers (PCs). However, a well-managed RL network contributes to reduction in cost of procurement, recovery, disposal, inventory holding and transportation and, additionally, contributes to an increase in customer loyalty and provides an advantage over competitors [15].

In this study, a multi-objective mixed integer programming model is developed for WEEE considering the requirements set by Ministry of Environment and Urbanization WEEE Directive. The contribution of the study is that the model incorporates illegal scrap dealers collecting WEEE into the network. Also, this model is designed according to the WEEE Directive of Turkey. In addition, three aspects of sustainability (economic, environmental and social) are used as base and three objective functions are defined. The first objective function is pertain to overall profit of the system. The second objective function reflects the environmental performance of network by minimizing total CO_2 emission. The third objective function is related with employment.

This thesis is organized as follows: Chapter 2 consists of two parts. The background for RL is provided in the first part, while the second part mention WEEE problem as global and local issue in general manner. Chapter 3 provides details about the setting of problem and the proposed model. The results of the implementations are shared in Chapter 4. In the final chapter, this thesis study is concluded by referring to accomplishments for the thesis and the ideas for the future studies are provided.

Chapter 2

Literature Review

In this chapter, the studies under the umbrella of RL literature and the ones associated with RL will be presented. Reverse Logistics Network Design (RLND) studies are fundamental part of RL literature.Various RLND studies are analyzed and an overview of some existing RLND problems are introduced.

Following key words are utilized while searching relevant studies: "reverse logistics", "reverse logistics network design", "green logistics network design", "reverse supply chain", "network design for recovery of WEEE" either in their titles or in the abstracts.

2.1 The Context of Reverse Logistics

Researchers have defined reverse logistics in different ways by emphasizing various aspects and the content of reverse logistics has been consequently maturing with respect to changing needs of humanity.

The origin of this evolving field is built on discussion regarding material recycling or disposal of products around the 1970s. It is possible to encounter with terms "Reverse Channels" or "Reverse Flow" in these studies [16, 17]. In the later times, Murphy and Poist [18] have used terms "backward flows" and "retro movements" which were closer to reverse logistics (RL) in terms of content. The most significant feature of this study is that indicating traditional supply chain flows as forward, and reverse logistics as backward flows [19]. The first known definition of RL was denoted by The Council of Logistics Management (CLM) [20]: "The term often used to refer to the role of logistics in recycling, waste disposal, and management of hazardous materials; a broader perspective includes all relating to logistics activities carried out in source reduction, recycling, substitution, reuse of materials and disposal.". Pohlen and Farris [21] defines RL with marketing approach: "...the movement of goods from a consumer towards a producer in a channel of distribution.". Kopicki et al. [22] have maintained the idea of opposite flow of traditional supply chain and stressed the importance of information regarding the flow: "Reverse Logistics is a broad term referring to the logistics management and disposing of hazardous or non-hazardous waste from packaging and products. It includes reverse distribution which causes goods and information to flow in the opposite direction of normal logistics activities.". Rogers and Tibben-Lembke's [23] definition is one of the most accepted definitions of RL. They have broadened the term by emphasizing goal and processes of logistics activities: "The process of planning, implementing, and controlling the efficient, cost-effective flow of raw materials, in-process inventory, finished goods, and related information from the point of consumption to the point of origin for the purpose of recapturing value or proper disposal." Carter and Ellram [24] emphasizes the opportunity of reverse flow that leads to resource reduction due to upstream movement of goods and materials.

When one mentions term "reverse logistics", it is possible to counter with other relevant terms and definitions such as "green logistics", "closed-loop supply chains" and "waste management". As Melissen and de Ron [25] state that these competing terms are open to misconception for researchers and practitioners. While forward logistics deals with all logistics activities associated with raw materials, components and products, reverse logistics is a system of logistics activities involving returned materials, components or products. In an integrated system, it is hard to separate forward and reverse logistics activities. Moreover, a combined system has own advantages for firms. For this reason, a new term "Closed-Loop Supply Chain (CLSC) has emerged. This concept inserts material recovery activities in a unified supply chain. The benefit of CLSC idea is that the design of a combined system considering both forward and reverse flow at the same time. In the following section, the relationship between RL and CLSC will be discussed in detail.

2.1.1 Relationship between Reverse Logistics and Closed Loop Supply Chains

The final node of traditional forward supply chain is customers. However, return activities allowing capturing additional values to manufacturers are included in closed loop supply chains. In this manner, reverse flow management can be perceived as an extension of the traditional supply chains with used product or material either returning to reprocessing organizations or being discarded [26]. Thus, closed loop supply chains emerge traditional supply-chain processes and additional reverse supply chain activities. These activities are summarized as following: acquiring the products coming from end-user, organizing movements of used products from the end points to disposal points. The next steps are testing, sorting and disposal procedures of the products according to their conditions and sending products for reuse, repairing, remanufacturing or recycling if they are in good condition and obtaining most cost-effective option among all the scenarios at the end. The final activity is coordination of marketing and distribution activities of refurbished products [27].

Due to reverse logistics activities in a holistic network, firms may have a chance to reach more cost-effective and environmentally friendly structure by the reuse of materials. Moreover, it is possible to satisfy customer needs while improving cost efficiency of firm. HP, Kodak, Xerox and Dell are the firms saving raw materials by practicing product recovery [28, 29]. As Rodriguez et al. [30] suggest that national and local authority should support the reverse logistics practices to facilitate the acquisition of production inputs and raw materials and to decrease the damage to environment during the product life cycle.

There are two options for firms to manage reverse flows. Various researchers study the two ways that the first one is combining forward and reverse distribution services by utilizing in-house distribution centers, while the second one is to benefit from centralized return centers (CRSs) [26, 31]. Both Rogers and Tibben-Lembke [23] and Gooley [31] highlight the role of CRCs for firms and discuss the advantage of an independent facilities in a central location providing service for returned products. The first advantage is obtaining more efficient system in sorting and repacking procedures because of large amount of quantities accumulated in the central location [31, 22]. Similar reasoning with the first one, firms may possess some assets with special features due to central return centers [32]. Another benefit of the return center is that it gives managers and employees the opportunity to concentrate on relevant problems regarding the returns in addition to the forward supply chain issues [23, 31]. Moreover, incentives, objectives and outcomes can be precisely attributed to the centralized return centers [31]. If the number of returns is excessive, varied options for disposition are required and then managers can increase their expertise. Even though a centralized system is beneficial for firms as mentioned above, the decision of inventing a central return center is challenging and various factors such as the strategic priorities of the reverse supply chain, regulations, product features, the number of returned products, transportation an disposal costs and different disposition alternatives must be considered [23, 31].

2.1.2 Literature on CLSC and RL

In this section, both reverse logistics and closed loop supply chain network design studies and the related literature will be discussed. The related studies can be categorized according to their network structures, objectives, decisions, uncertainties, solution methods, recovery options and remanufacturing alternatives.

Some researchers pay attention how RL and CLSC literature evolve according to recent technological advancements, directives, social issues etc. These studies give an opportunity to learn stages of development of these areas. Huscroft et al. [33] shares an article especially for recent supply chain professionals who run reverse logistics activities. The study mentions seven key issues of today's RL by using Delphi Method: customer support, top-management support, communication, cost, formalization, timing of operations and environmental issues. At the end of the study, suggestions for future research are presented for both professionals and scholars.

Another study conducted by Ye and Zhenua [34] is based on RL literature published after 2000. They reveal that the most of the studies concentrate on modeling of reverse logistics network design (RLND) which is very small portion of RL literature. Moreover, RLND studies focus on case study, especially on electrical and electronic equipment recycling. In this literature review, they focus on the quantitative models in RLND and classify these models as closed-loop network model, generic model, stochastic model and 3PLs model.

Govindan and Soleimani [35] shares a comprehensive literature review of articles published in only Journal of Cleaner Production (JCP) which is well-esteem journal in this area. This study includes 83 accepted online papers published up to 31 December 2014 in fields of RL and CLSC and provides a systematic view of previous studies. The papers are categorized according to their content and trend issues in these fields and then future research opportunities are revealed.

Souza [36] presents a study which is both a review and tutorial of the literature on CLSC including reverse flow of used products from customers to manufacturers. In this manner, leasing and remanufacturing options are mentioned for supply chains. The author splits the literate into three basic mainstreams which are strategic, tactical, and operational issues. However, the main concern is strategic one including decision of remanufacturing for original equipment manufacturer (OEM), take-back applications based on legislations, network design etc., and tactical ones such as product acquisition from consumers and disposition decisions. Beneficial side of this article is that problems are presented with a base model and all assumptions, primary results and possible future extensions.

Agrawal et al. [37] conduct another research on RL literature that contains 242 published articles to point out the gap in the literature. They suggest that even though the field of RL improves by valuable researchers, some issues such as implementation of regulations, forecasting for product returns, outsourcing options, RLND considering secondary markets and disposition decisions are not extensively analyzed yet.

The publication of Bazan et al. [38] is another beneficial review paper in the field of RL focusing on mathematical inventory models. In this study, the inventory systems of chosen articles are based either on the economic order/production quantity (EOQ/EPQ) or the joint economic lot size (JELS) settings. The classification of articles is done according to modeling assumptions and indicators for green inventory and supply chain as well. At the end, it is mentioned that waste disposal, greenhouse-gas emissions and energy consumption during production issues are important for future RL models. Moreover, an example of a RL inventory model with environmental implication is shared so as to strengthen the argument.

Up to this point, some selected literature review papers presented. In the following, various modeling studies will be introduced.

Govindan et al. [39] study a sustainable multi-echelon, multi-period, multi-objective reverse logistics network design model in order to decrease the environmental impact and present value of overall cost and to enhance the social responsibility as well. For this reason, this study involves three purposes of sustainability. In this study, authors utilize fuzzy mathematical programming to cope with uncertain parameters and Pareto front solutions are attained by applying customized multi-objective particle swarm optimization (MOPSO) algorithm. Validity control is conducted by using both small and large size problems that are based on comparison metric and computational time according to analysis of variance. Authors suggest that the proposed algorithm gives better solutions than epsilon-constraint in terms of both computational time and qualified solutions.

Alshamsi and Diabat [40] propose a mixed-integer linear program (MILP) deciding on the operating inspection centers and remanufacturing plant and the capacities of them. One diversifying feature of this model is that it provides two different transportation options which are utilizing in-house fleet and outsourcing option. Initial investment located in the beginning of the time horizon is defined for expenses for fleet and capacity expansion decision for the later periods. The proposed model is applied on a real-life case and illuminating results for both decision makers who are parts of both governmental and private organizations are reported.

Kılıç et al. [2] construct a mixed integer linear programming model for WEEE generated in Turkey. In this study, 10 different scenarios whose different collection rates are designed, and various types of recycling facilities and storage cites are considered as distinct from other studies in the literature. The lowest rates required recycling are determined according to the European Union Directive by considering product categories as well. This study is a case study which gives optimal locations for both storage sites and recycling facilities.

Another network design study is done by Ayvaz et al. [41] for a third-party WEEE recycling firms to maximize profit. They propose a generic multi-echelon, multi-product and capacity constrained two stage stochastic programing model for reverse logistics network considering three types of uncertainty which are return quantity, return quality and transportation cost. The proposed model is applied to a WEEE recycling firm in Turkey and is solved by using sample average approximation method. They indicate that the proposed two stage stochastic programming model gives sufficient results even the model including uncertainties.

Kannan et al. [42] developed a mixed integer linear programming model that purpose decreasing effect of reverse logistics activities on climate change. In this study, CO_2 foot print is chosen as a factor that triggers climate change. Thus, the overall cost desired to be minimized includes the cost of CO_2 emissions as well. The model dealing with location and transportation issues provides the decisions for reverse logistics activities regarding recovery of used products. A real problem from plastic sector is used for the validation of the proposed model.

Millet [43] focus on alternative reverse logistics channels that can feed the production process with reusable modules. This study provides 18 generic RL channel structures differentiating according to the location of treatment activities in the RL network and the proposed structures promise lower environmental effect and greater economic return.

Achillas et al. [8] stress out the fact that WEEE is categorized as hazardous waste and the management of this growing waste stream is taken serious by developed countries. They suggest that the effective management of the issue requires both adequate legislations and well-coordinated collaboration of actors in the RL network. The main purpose of this study is to present such a decision support tool allowing both policy-makers and regulators to create optimal RL network for WEEE. In relation to this coordination, they generate a MILP model that consider collection points and recycling facilities as well. The proposed model is applied on Region of Central Macedonia, Greece.

Listeş and Dekker [44] study on a RL network design problem for recovery of sand generated during demolition in the Netherlands. The model includes uncertain parameters, namely, demand locations and supply demand. Two-stage stochastic programming and three-stage stochastic programming approaches are used to formulate the problem. The first stage is to find out required investment to open a facility before achieving actual realizations of the random parameters, while the second stage is related with the allocation of flow on the determined network after the values of uncertain parameters are revealed. Maximization of the expected net profit is the objective of the model and calculated by subtracting facility opening, transportation and processing costs from revenue earned by selling clean or half-clean sand. The model is solved with a commercial solver (CPLEX) and results show that the scenarios with higher demand make the network more flexible regarding demand location.

In the study of Yu and Solvang [45], a stochastic optimization model intending low carbon emission is designed. The model corresponds to a single-period multi-product multi-level reverse logistics network and government supports the system with supplying subsidy used for landfill process of end of use produces and enhancing recovery activities. Selected method for the problem whose aim is to maximize the profit is a modified multi-criteria scenario-based approach. The model also tries to eliminate unstable decision due to uncertainty in end of use products generated from customers and selling price of the recovered produces as well. The model is tested under various emission levels and the results show that if emission values decrease, the profit of the system decreases.

Another network design model including both forward and backward flow is studied by El-Sayed et al. [46]. The model is designed in a multi period and multi echelon setting by considering risk factor. The model has two stochastic parameters that the first one is demands in customer locations and the second one is the return quantities. Thus, a stochastic mixed integer linear programming (SMILP) is used for formulation of the problem and the model is applied, then the results of the application shows that mean of demand and return ratio of products have a quite serious impact on the objective.

2.1.3 The role of Sustainability in RL and CLSC Literature

It can be observed that many studies in the field of RL and CLSC literature is motivated by the idea of sustainability implicitly or explicitly. In this manner, researchers build the objectives of their models on the three pillars of the sustainability (economic, social, environmental). The studies based on sustainability may include three, two or just only one of them. In the following sections, the various objectives in both RL and CLSC literature regarding the three pillars of the sustainability will be shared, respectively.

Economic Objectives of RL/CLSC Network Design Models

In RL/CLSC literature, the most common objective is expectedly the one reflecting financial concerns. Despite both professionals and researchers take the environmental and/or social objectives into account, the economic side of the problem is non-negligible. However, researchers can include different types of cost components in their models. Govindan et al. [35] summarize some of these cost components mentioned in a part of supply chain literature: location cost of facilities (even closing operating facilities [9]), operating cost of active facilities, operating costs of working facilities, inventory holding cost, transportation/shipment cost, production/manufacturing/remanufacturing costs, processing costs, procurement costs, technology selection costs, shortage/backorder costs, recovery activities costs, penalty costs and incomes gained.

Environmental Objectives of RL/CLSC Network Design Models

Environmental objectives are not diversified in a wide range yet. Accorsi et al. [47] design a carbon based objective function to minimize CO_2 emission for a closed-loop network. Similarly, Kafa et al. [48] defines an objective minimizing greenhouse gas emissions. In the study of Zhalechian et al. [49], the objective function regarding environmental concern consists of environmental impact of CO_2 emissions and fuel consumption considering features of vehicles, road and air conditions and the carried load by vehicle. Moreover, the wasted energy while vehicles wait for receiving services in remanufacturing centers is considered as environmental impact. Amin and Zhang [50] list the environmental criteria for supplier selection problem such as reflecting waste reduction, environmental technology usage, environmental friendly material usage, pollution reduction capability, energy consumption. Govindan et al. [39] pay attention to environmental impact of transportation, processing of product, recycling of materials and incineration activities for the environmental objective of their model.

Social Objectives of RL/CLSC Network Design Models

This category is the one that is open to improvement the most among all three. Zhalechian et al. [49] define an objective function consisting of two parts. The first part is related with job opportunities connected with the unemployment rate while the second one is related with the balanced economic development. The third objective of the model designed by Kafa et al. [48] is maximizing job opportunities occurred due to alliance between third-party providers and supplier. Govindan et al. [39] defines more comprehensive social objective function including the number of job opportunities which is common in the literature. The model considers the possible working accidents and counts the average number of lost days due to the accidents. Moreover, it is also stressed that technological differences in the collection centers cause difference in working conditions. Dehghanian and Mansour [51] defines a social objective having four dimensions: the number of employment, potential damage to worker caused by hazardous environment, product risk and local development.

2.2 WEEE as a Global Issue

In the previous sections, some of RL and CLSC network design problems were provided. Researchers have applied their model on various sectors and products. WEEE is one of the product types attract attention due to the reason why WEEE contains both recyclable materials and hazardous materials inside. Therefore, a clear majority of researchers working on RL and CLSC pay attention WEEE issue. In the rest, the following subjects will be mention: which materials included in WEEE, how WEEE can be harmful for human life, especially for workers, how governments deal with the problem and how Turkish government against the issue.

2.2.1 The Categories of WEEE

There are ten different types of WEEE accepted in the worldwide [2]:

- Large household appliances
- Small household appliances
- IT and telecommunications equipment

- Consumer equipment
- Lighting equipment
- Electrical and electronic tools
- Toys, leisure and sports equipment
- Medical devices
- Monitoring and control instruments
- Automatic dispensers

All those categories include various types of materials inside. For this reason, it is hard to manage the waste stream for electrical and electronic equipment. Due to wide diversification in the materials inside WEEE, it is hard to consider all of them in research studies. Ferrous metals, non-ferrous metals, glass, plastics and some other materials are mainly taken into consideration . It can be roughly said that more than the half of the weight consist of iron and steel while around 20% of the weight is plastic as shown in Figure 2.1.

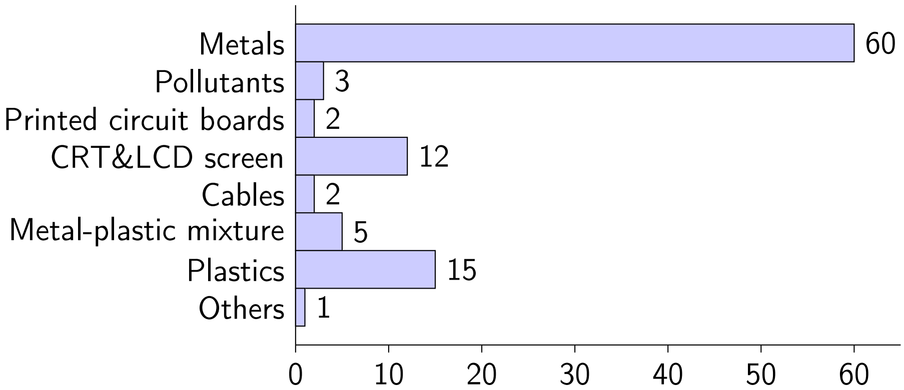

Figure 2.1: Percentage of materials inside WEEE [1]

Proper disposal and recycling activities are critique to capture valuable metals such as gold, copper and silver. Nevertheless, poor practices lead to harmful impacts on both environment and human health due to toxic content of WEEE such as heavy metals (Pb), polybrominated diphenyl ethers (PBDEs), polychlorinated and polybrominated dioxins and furans (PXDD/Fs). Sepúlveda et al. [52] summarized that ways that the toxic content can be released involuntarily:

- Leachates from dumping activities
- Particulate matter from dismantling activities
- Fly and bottom ashes from burning activities
- Fumes from mercury amalgamate "cooking", desoldering, and other burning activities
- Wastewater from dismantling and shredding facilities
- Effluents from cyanide leaching, other leaching activities or mercury amalgamation

As can be deduced that, recycling workers are directly involved in these processes. Especially, the informal workers in developing countries are in danger due to poor conditions because they manage the larger part of WEEE recycling operations. In the literature, there are several studies showing the tangible effect of toxic substances on workers. Sepúlveda et al. [52] review the research studies in China and India, where illegal recycling operations are very common, illustrating the effects of hazardous substances included in WEEE. This review shows that it is required to have developed mechanism to control illegal recycling activities in China and India. Moreover, they suggest that the number of population increase, the informal recycling activities will increase correspondingly. Therefore, informal WEEE stream must be a part of formal activities instead of eliminating them as also suggested in this thesis study.

2.2.2 Legal Steps to Manage WEEE Problem

WEEE is a global issue and countries/organizations have own directives to manage the problem. The amount of hazardous materials included in WEEE is decreasing because of increasing consciousness and legislations. However, it is still a fundamental issue in waste management. One fundamental directive is Restriction of Hazardous Substances Directive (RoHS 2002/95/EC) [53] which limits the usage of lead, cadmium, mercury, hexavalent chromium, polybrominated biphenyl (PBB) and polybrominated diphenyl ether (PBDE) flame retardants inside the products placed on EU market (European Union, 2003a). Another directive set by European Union is The Energy Using Products Directive [54]. This directive supports environmental development in terms of energy efficiency in addition to the content of products (European Union, 2005). The most well-known directive of EU regarding WEEE is The WEEE Directive (Directive 2002/96/EC) which holds the manufacturers and importers in the EU member states responsible to collect and to organize the environmental disposal of the products came back from customers. In Japan, The Home Appliance Recycling Law (HARL) is introduced in April 2001. The purpose of this law is to deal with four important types of WEEE sources which are refrigerators, washing machines, TVs and air conditioning units [1]. The content of the law is enlarged in April 2009 and LCD, plasma TVs and clothes dryers are included as well. After this program, recycling rates and recovery rates are increased. Moreover, manufacturers and importers are forced to retrieve their products like the WEEE directive of EU. Also, they are required to dismantle and recover the both components and materials [1].

2.2.3 Current Situation Regarding WEEE in Turkey

The main aim of the regulations mentioned in previous sub-section is to reduce the amount of WEEE generated, to increase recycling practices and to increase the environmental performance of all stakeholder [11]. The current regulation in Turkey is Waste Electrical and Electronic Equipment (WEEE) Directive" come into force in May 2012. This directive clearly defines the obligations of stakeholders in a manner similar to other examples in the world but there are also scrap dealers who illegally collect and process WEEE (as shown in Figure 2.2). Since the processes for handling WEEE are far below the standards that should be, there is a serious threat to human health and the environment, especially the scrap dealers themselves. In addition, the economic performance of the system is also decreasing because the economic components of electrical and electronic goods cannot be recycled. For this purpose, it is required that to make formal those illegal WEEE business [55]. Informal sector is not the only problem that Turkey encounter in management of WEEE. In the directive, collection targets are clearly indicated in Table 2.1. Nevertheless, Turkey is behind the collection targets since collection infrastructure is not adequate. In addition, technical and financial capacities of WEEE treatment facilities are insufficient [11].

Table 2.1: WEEE collection target per capita set by Turkish Directive.

Waste Collection Target by Year (kg/capita-year)						
	EEE Categories	2013	2014	2015	2016	2018
1	Refrigerators/Cooling/Air-conditioning appliances	0.05	0.09	0.17	0.34	0.68
2	Large white appliances (with the exception of refrigerators/cooling/air-conditioning appliances)	0.1	0.15	0.32	0.64	1.3
3	Televisions and monitors	0.06	0.1	0.22	0.44	0.86
4	IT and telecommunication & consumer equipment (with the exception of televisions and monitors)	0.05	0.08	0.16	0.32	0.64
5	Lightning equipment	0.01	0.02	0.02	0.04	0.08
6	Small household appliances, electrical and electronic tools, toys, sports and leisure equipments, monitoring and control tools	0.03	0.06	0.11	0.22	0.44
	Total Household WEEE (kg/capita-year)	0.3	0.5	1	2	4

(a) A scrap dealer collects waste in the street

(b) An example of scrap dealer junk yard

Figure 2.2: A scrap dealer and view of a junkyard

Chapter 3

Problem Statement and Modeling

The efficient management of WEEE requires well-designed network structure that consists of collection points, pretreatment facilities, sorting facilities, treatment facilities, recycling facilities, disposal facilities and remanufacturing facilities in content of closed loop supply chains. We propose a multi-period, multi-product mixed integer linear programming model (MILP) for the reverse logistics network design of WEEE and the model is implemented to Istanbul city. The proposed network is designed according to current situation of WEEE management stream of Turkey and requirements of WEEE directive as well. The network consists of collection points, WEEE treatment facilities, second hand materials buyers, disposal facilities and scrap dealer junkyards. The model provides powerful insight about opportunity if WEEE is collected and treated appropriately. In this chapter, details of the model and proposed network will be explained in detail.

The organization of this chapter is as follows: structure and characteristics of the proposed network will be shared in Section 3.2. Section 3.3 explains the details of mathematical model while section 3.4 provides the mathematical formulation of problem.

3.1 Network Representation

WEEE in the category of hazardous waste must follow a long route starting from waste generation points and ending with disposal facilities or recycling facilities. Fundamental elements of this comprehensive network are waste collection points, sorting facilities, recycling/recovery facilities, disposal facilities. In addition

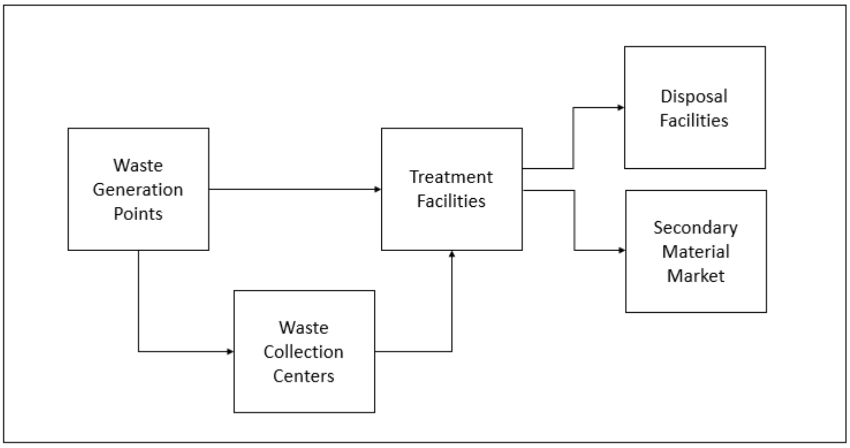

Figure 3.1: Ideal network based on directive

to these participants, remanufacturing facilities that utilize the reusable components in WEEE may take place in reverse logistics networks. In this thesis, facts of WEEE recovery network in Turkey is considered. To the best of our knowledge, there is no WEEE sorting facility/area where wastes are classified according to their conditions and there is no such a facility running remanufacturing activities actively. Therefore, the model does not include these two elements to build a more realistic picture of WEEE management in Turkey.

Turkish directive states yearly collection targets of household WEEE per capita. This study only considers household WEEE instead of industrial WEEE. It is assumed that city centers are waste generation points and the quantity of WEEE occurred in a city is directly proportionate to population of the city. In other words, the amount of WEEE to be collected according to population of each city is assumed to occur in town centers in the beginning of each time interval for the sake of simplicity. Two options are available for generated WEEE in compliance with the directive: The waste may be directly transferred to WEEE treatment facilities without waiting in collection points or first accumulated in collection points and transported to the treatment facilities later as depicted in Figure 3.1. In addition to these two routes, third one exists due to the scrap dealers collecting WEEE illegally.

Municipalities and EEE distributors are held responsible for the collection of WEEE by the directive. In this manner, municipalities are required to build collection center to accumulation of the waste while EEE distributors have to keep collection boxes or containers in accordance with the size of the place or reserve

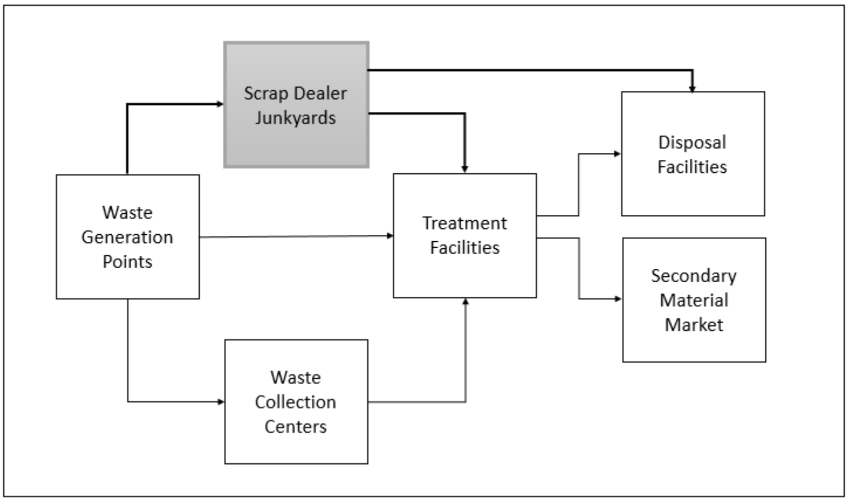

Figure 3.2: Proposed network for the reverse logistics of WEEE

closed part inside shop. Two types of collection center have limited holding capacities.

The fundamental actor of this network is treatment facilities. They receive WEEE from collection points, collection points and subsidized scrap dealer junkyards. Each type of WEEE need special treatment processes to separate both hazardous and recoverable contents. Hazardous materials are sent to disposal facilities while recoverable materials are sold to secondary material buyers.

Scrap dealers are problematic side of WEEE management system of Turkey. They collect WEEE with their own trucks, dismantle them by using improper techniques and sell the materials. Since they are not well-equipped for handling of waste, they are open to be exposed to hazardous content of waste. Moreover, capability to extract recoverable materials is quite low due to lack of qualified treatment. These unsuitable activities cause loss of national wealth as well. To overcome this issue, new network model including scrap dealers and their junkyards is prosed in Figure 3.2. In this network, the junkyards are supported by governmental subventions with respect to limited funds.

3.2 Model Explanation

The model is designed as multi objective and multi period. The decisions are made in the beginning of these time periods. For this study, since we assume that the amount of waste to be collected with respect to the population occurs in district centers, the costs related with waste collection activities are ignored. It is also assumed that collection centers have stationary holding capacity and WEEE treatment facilities and subsidized junkyards have constant handling capacity through the planning horizon. Therefore, it is deduced that any collection center or any facility or any WEEE junkyard in this model does not hold inventory in the end of time periods. There are two types of collection points: the one that municipalities build and the reserved area in EEE distributors in their stores. Locations of candidate WEEE facilities and junkyards are known in advance. In addition, the amount of recoverable material to be sold to secondary material buyers is unlimited. Finally, if a junkyard is subsidized, it becomes a proper sorting facility where wastes are classified according to their condition and are sent to disposal facility directly.

This model has three objectives focusing on profit, environmental impact and social benefit of the whole WEEE recovery system respectively. The questions answered in this study can be summarized as follow:

- Which WEEE treatment facilities are opened in each time period
- Which scrap dealers junkyards are incorporated into the waste stream in each time period
- How much waste to transport from waste generation points to scrap dealer junkyards, WEEE treatment facilities and WEEE collection points
- How much recoverable material to transport from WEEE treatment facilities to secondary material buyers and monetary value of recovered materials
- How much waste to transport from WEEE treatment facilities and scrap dealers junk yards to disposal facilities
- How many workers are employed in WEEE treatment facilities
- How many scrap dealers are became legal worker after subsidization of junkyard
- Total cost of transportation, disposal, sorting/handling activities and total investment amount to open WEEE facilities and subsidization of junkyards

- CO_2 emission caused from transportation, disposal and building new WEEE facility

3.3 Mathematical Formulation

In this section, parameters and decision variables of multi-objective mixed integer programming model will be introduced first. Afterwards, the model will be provided and objective functions and constraints will be described. Notations of the model is as follows:

G	Set of waste generation points
g	Index of waste generation points $g = \{1, .., G\}$
P	Set of WEEE
p	Index of WEEE $p = \{1, .., P\}$
C	Set of waste collection points
c	Index of waste collection points $c = \{1, .., C\}$
F	Set of waste treatment facilities
f	Index of waste treatment facilities $f = \{1, .., F\}$
D	Set of disposal facilities
d	Index of disposal facilities $d = \{1, .., D\}$
B	Set of secondary material buyers
b	Index of secondary material buyers $b = \{1, .., B\}$
T	Planning horizon
t	Index of time periods $t = \{1, .., T\}$
M	Set of materials inside products
m	Index of materials inside products $m = \{1, .., M\}$
S	Set of illegal junkyards operated by scrap dealers
s	Index of illegal junkyards operated by scrap dealers $s = \{1, .., S\}$
R_{gpt}	Amount of estimated waste for product p to be generated in region g in period t
c_i	Handling/sorting/collection capacity of WEEE treatment facility i or junkyard s or collection point c
tc^x_{ijp}	Transportation cost of product p from site i to site j, $(i, j) \in K$

tc^{y}_{ijm}	Transportation cost of material m from site i to site j, $(i,j) \in L$
dc_{dt}	Disposal cost of disposal facility d in period t
fc_{ft}	Fixed cost of opening facility f in period t
rv_{bmt}	Monetary value of material m sold to secondary material buyer b in period t
h_{pit}	Handling cost of product $p \in P$ in facility $i \in F$ or subsidized junk yard $i \in S$ in period t
sub_{st}	Required subsidy to subsidize scrap junk yard s in period t
q_{pm}	Rate of recoverable material m inside product p
bi_t	Total usable subsidy for scrap dealer junk yards in period t
e_i	Environmental impact of transporting product $i \in P$ or material $i \in M$
ed	Environmental impact of disposing hazardous waste
eo	Environmental impact of opening a new facility
$w1_f$	Number of required worker when facility f is opened
$w2_s$	Number of scrap dealer working in junk yard s
α_p	Waste distribution percentages

Available channel for the flow of product p

$K = \{(i,j) : (i \in G \wedge j \in C) \cup (i \in G \wedge j \in F) \cup (i \in C \wedge j \in F) \cup (i \in G \wedge j \in S) \cup (i \in S \wedge j \in F) \cup (i \in S \wedge j \in D)\}$

Available channel for the flow of material m

$L = \{(i,j) : (i \in F \wedge j \in D) \cup (i \in F \wedge j \in B)\}$

Notations employed for decision variables are as follow:

x_{ijpt}	Amount of waste p transported from site i to site j, $(i,j) \in K$, in period t
y_{ijmt}	Amount of material m transported from site i to site j, $(i,j) \in L$, in period t

$$v_{ft} = \begin{cases} 1 & \text{if WEEE treatment facility } f \text{ is opened in period } t \\ 0 & \text{otherwise} \end{cases}$$

$$z_{st} = \begin{cases} 1 & \text{if junk yard } s \text{ is subsidized in period } t \\ 0 & \text{otherwise} \end{cases}$$

Objective functions are as follows:

- Profit-based objective

$$\max W_1 = \sum_{i\in F}\sum_{j\in B}\sum_{m\in M}\sum_{t\in T} rv_{jmt}\cdot y_{ijmt} - \sum_{(i,j)\in K}\sum_{p\in P}\sum_{t\in T} tc^{x}_{ijp}\cdot x_{ijpt}$$
$$- \sum_{(i,j)\in L}\sum_{m\in M}\sum_{t\in T} tc^{y}_{ijm}\cdot y_{ijmt} - \sum_{i\in G}\sum_{j\in S}\sum_{p\in P}\sum_{t\in T} x_{ijpt}\cdot h_{pjt}$$
$$- \sum_{j\in F}\sum_{p\in P}\sum_{t\in T}\Big(\sum_{i\in G} x_{ijpt} + \sum_{i\in C} x_{ijpt}\Big)\cdot h_{pjt}$$
$$- \sum_{j\in D}\sum_{t\in T}\Big(\sum_{i\in S}\sum_{p\in P} x_{ijpt} + \sum_{i\in F}\sum_{m\in M} y_{ijmt}\Big)\cdot dc_{jt}$$
$$- \sum_{f\in F}\sum_{t\in T} fc_{ft}\cdot v_{ft} - \sum_{s\in S}\sum_{t\in T} sub_{st}\cdot z_{st} \tag{3.1}$$

- Environmental objective

$$\min W_2 = \sum_{(i,j)\in K}\sum_{p\in P}\sum_{t\in T} et_p\cdot x_{ijpt} + \sum_{(i,j)\in L}\sum_{m\in M}\sum_{t\in T} et_m\cdot y_{ijpt} + \sum_{f\in F}\sum_{t\in T} eo\cdot v_{ft}$$
$$+ \sum_{j\in D}\sum_{t\in T}\Big(\sum_{i\in F}\sum_{m\in M} y_{ijmt} + \sum_{i\in S}\sum_{p\in P} x_{ijpt}\Big)\cdot ed \tag{3.2}$$

- Social benefit oriented objective

$$\max W_3 = \sum_{f\in F}\sum_{t\in T} w1_f\cdot v_{ft} + \sum_{s\in S}\sum_{t\in T} w2_s\cdot z_{st} \tag{3.3}$$

s.t.

- Flow balance constraints

$$\sum_{f\in F} x_{gfpt} + \sum_{c\in C} x_{gcpt} + \sum_{s\in s} x_{gspt} = R_{gpt},\quad \forall g\in G, \forall p\in P, t\in T \tag{3.4}$$

$$\sum_{g\in G} x_{gspt}\cdot\alpha_p = \sum_{j\in D} x_{sjpt},\quad \forall p\in P, s\in S, t\in T \tag{3.5}$$

$$\sum_{g\in G} x_{gspt}\cdot(1-\alpha_p) = \sum_{j\in F} x_{sjpt},\quad \forall p\in P, s\in S, t\in T \tag{3.6}$$

$$\sum_{g\in G} x_{gcpt} = \sum_{f\in F} x_{cfpt},\quad \forall c\in C, \forall p\in P, \forall t\in T \tag{3.7}$$

$$\sum_{p\in P}\big(\sum_{i\in G}x_{ijpt}+\sum_{i\in C}x_{ijpt}+\sum_{i\in S}x_{ijpt}\big)\cdot q_{pm}=\sum_{b\in B}y_{jbmt},$$

$$\forall j\in F,\forall m\in M,\forall t\in T \tag{3.8}$$

$$\sum_{p\in P}\big(\sum_{i\in G}x_{ijpt}+\sum_{i\in C}x_{ijpt}+\sum_{i\in S}x_{ijpt}\big)\cdot\big(1-q_{pm}\big)=\sum_{d\in D}y_{fdmt},$$

$$\forall j\in F,\ \forall m\in M,\ \forall t\in T \tag{3.9}$$

- Capacity constraints

$$\sum_{g\in G}\sum_{p\in p}x_{gspt}\le z_{st}\cdot c_s,\quad \forall s\in S,t\in T \tag{3.10}$$

$$\sum_{p\in P}\big(\sum_{i\in G}x_{ijpt}+\sum_{i\in C}x_{ijpt}+\sum_{i\in S}x_{ijpt}\big)\le c_f\cdot v_{ft},\quad \forall f\in F,\forall t\in T \tag{3.11}$$

$$\sum_{g\in G}\sum_{p\in p}x_{gcpt}\le c_c,\quad \forall c\in C,t\in T \tag{3.12}$$

- Resource constraint

$$\sum_{s\in S}sub_{st}\cdot z_{st}\le bi_t,\quad \forall t\in T \tag{3.13}$$

- Continuity constraints

$$v_{ft-1}\le v_{ft},\quad \forall f\in F,\forall t\in T \tag{3.14}$$

$$z_{st-1}\le z_{st},\quad \forall s\in S,\forall t\in T \tag{3.15}$$

- Non-negativity and integer constraints

$$v_{ft}\in\{0,1\},\quad \forall f\in F,\forall t\in T \tag{3.16}$$

$$z_{st}\in\{0,1\},\quad \forall s\in S,\forall t\in T \tag{3.17}$$

$$x_{ijpt},y_{ijmt}\ge 0 \tag{3.18}$$

The objective function (3.1) maximizes the profit of activities. We initially sum the revenues of materials when sold to raw material buyers and then subtract total transportation cost, holding, handling, disposal cost of products or materials, the fixed cost of establishing a new WEEE treatment facility and required investment for subsidization. The second objective function (3.2) minimize the environmental impacts occurred due to transportation, disposal of materials and opening new treatment facility. The third objective function (3.3) is related to the social benefit. The purpose of this objective function is to maximize employment by including scrap dealers to secure their health and safety. Moreover, additional employment is also valid for new facilities to be opened. Constraint (3.4) distributes WEEE generated among junk yards, collection points and treatment facilities. Constraints (3.5) and (3.6) distribute additional WEEE collected by subsidized junkyards. Constraint (3.7) assures the flow balance at collection points while constraint (3.8) and (3.9) ensure the flow balance at treatment facilities. Constraints (3.10), (3.11) and (3.12) mean that the number of products to be processed cannot exceed capacity of junkyards, treatment facilities, collection points respectively. Constraint (3.13) is simply budget constraint of subsidy. Constraint (3.14) and (3.15) sustain the position of facilities and junk yards after opening and subsidy decisions. Constraints (3.16) and (3.17) indicates integer decision variables while (3.18) is non-negativity constraint.

Chapter 4

Computational Studies

In this section, the computational results of the proposed mathematical model will be presented. The model is designed as multi objective and three objective functions reflect three fundamental aspects regarding WEEE management issue. The defined objectives contradict with each other. For this reason, it is almost impossible to have a unique optimal solution because of the trade of between objective functions as usual in multi-objective optimization problems. The model has a generic structure and it is suitable to apply on different RLND problem settings with various sizes. In this thesis study, the proposed model has been applied on Istanbul city whose the highest population density in Turkey. The following procedure is applied: First of all, the model is solved for each objective function by using IBM ILOG CPLEX Optimization Studio 12.6 in a workstation with a 64-bit Windows 7 Professional operating system and 2.10 GHz processor . According to the results found separately, the ranges for each objective function are determined to construct the set of Pareto solutions. Within the set, there are dominated solutions that must be eliminated to achieve non-dominated solutions. The solutions performing worst in all objective functions are discarded. For detailed analysis, Pareto frontiers of pairwise combinations of the three objectives will also be provided.

4.1 Description of Data

The computational studies considers 39 districts of Istanbul. Since Adalar district is composed of several islands, the amount of generated waste in this district is added to Tuzla district for the sake of simplicity. Thus, there are 38 different waste

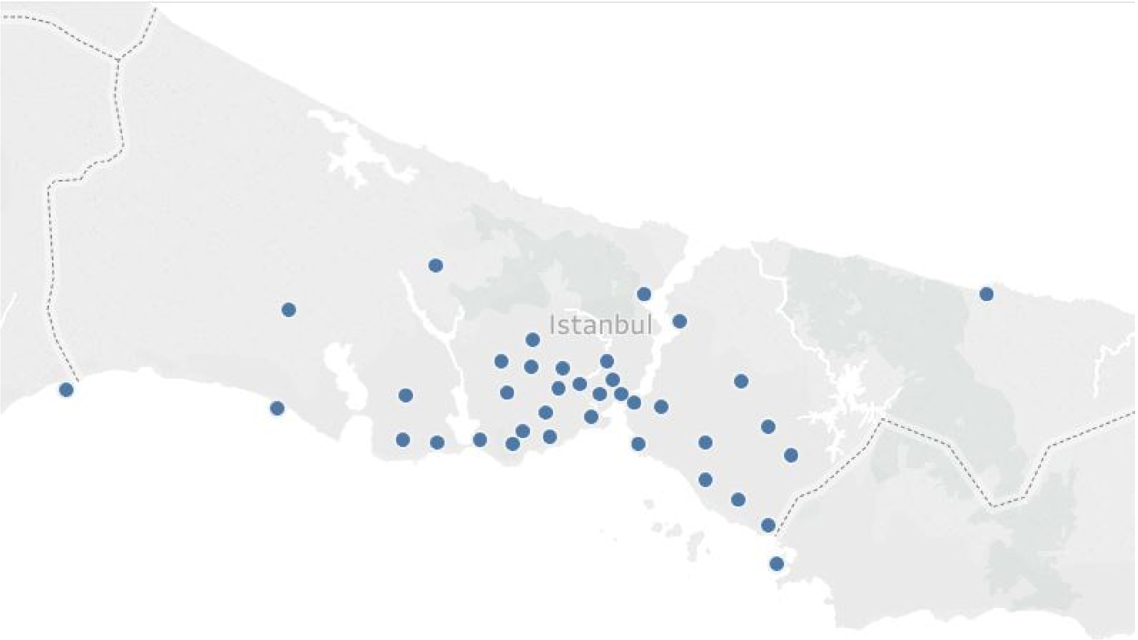

Figure 4.1: WEEE generation points

generation points, illustrated in Figure 4.1.

WEEE have three ways to follow after waste generation points. The first one is waste collection points. There are 644 collection points, depicted in Figure 4.5, that have different holding capacities. Secondly, some amount of waste may directly go to WEEE treatment facilities. As shown in Figure 4.2, 18 different WEEE treatment facilities are decided by considering population density and industrial zones. Also, it is quite common situation that the wastes can be collected by scrap dealers and go to junk yards. For this study, 40 different scrap dealer junkyard location are selected as illustrated in Figure 4.3.

There are 4 different disposal facilities illustrated in Figure 4.4. One of them is out of Istanbul. All of them do not accept all types of materials to be disposed.

The last actors of the network are secondary material buyers shown in Figure 4.6. There are 8 different buyers selected. They accept different type of secondary materials.

The amount of WEEE per capita that must be collected until 2018 is stated in the directive. In this thesis study, all decisions are made for 6 years period. It is assumed that the collection target for next year increases 0.5 kg. Also, we assume that the rate of population growth is 0.01 for every districts of Istanbul. There are 4 different types of WEEE considered in this study based on the directive: large

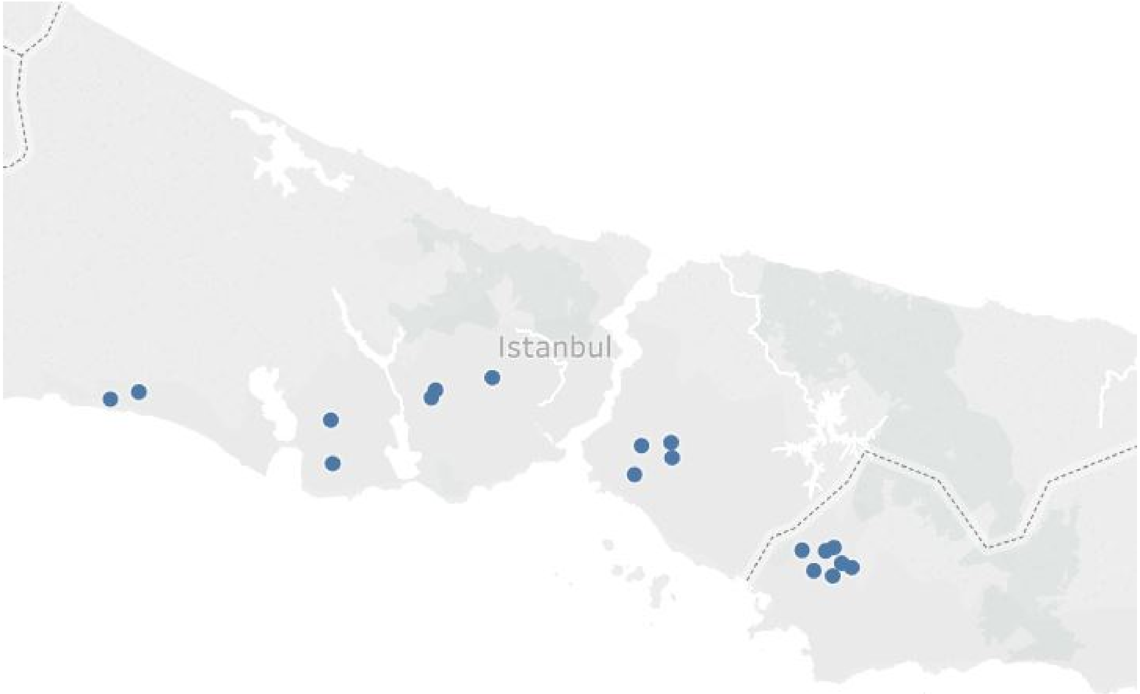

Figure 4.2: Selected WEEE treatment facilities

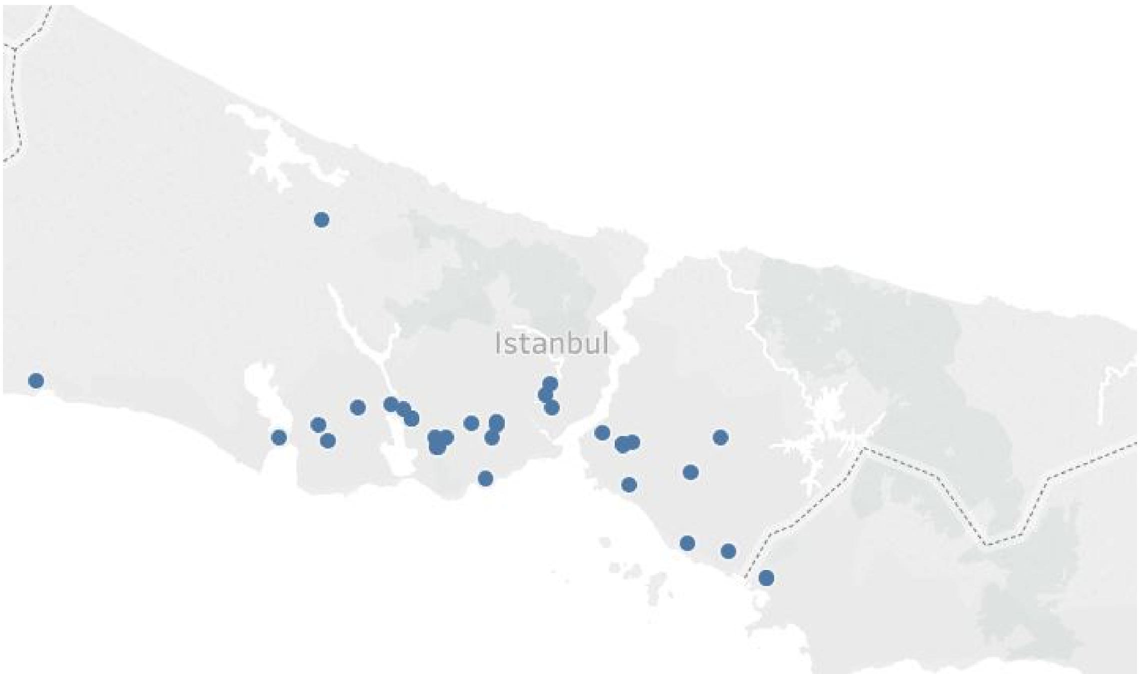

Figure 4.3: Scrap dealer junk yards

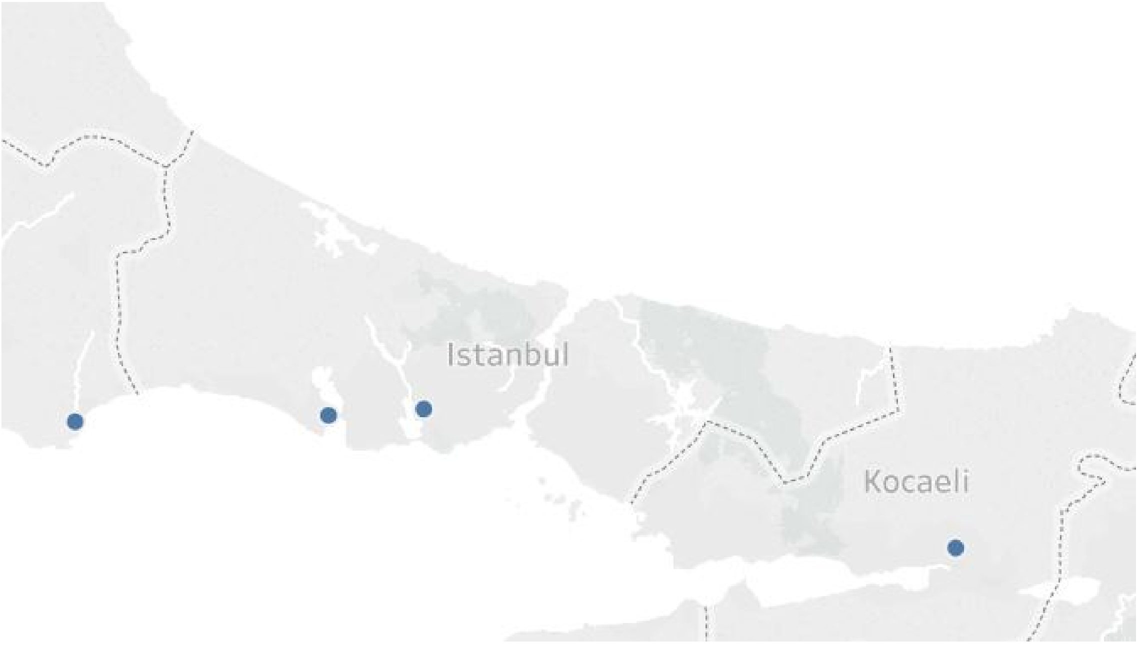

Figure 4.4: Disposal facilities

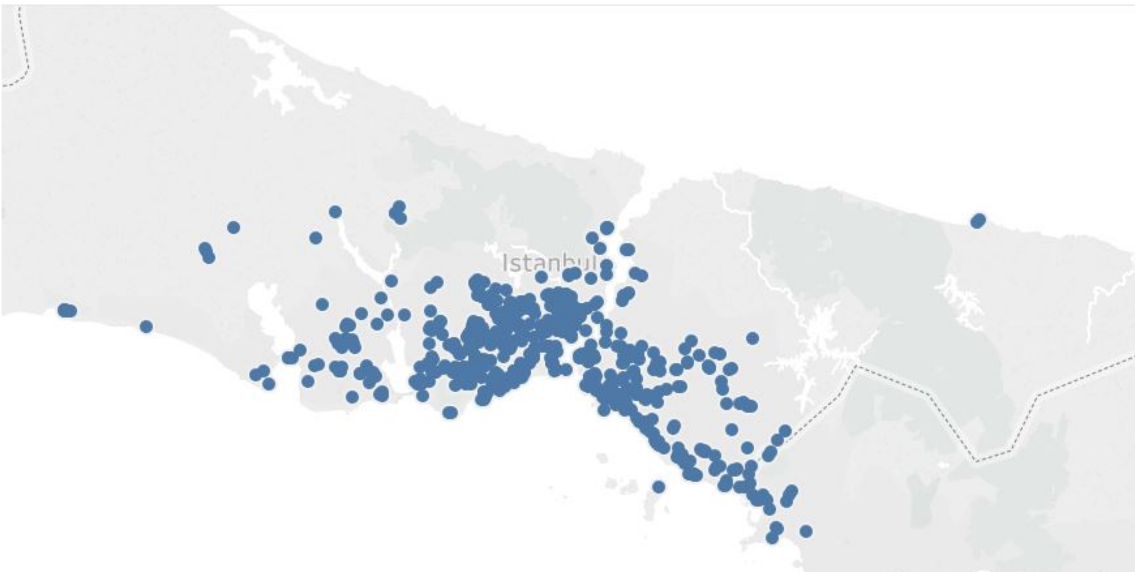

Figure 4.5: Collection centers

Figure 4.6: Secondary material buyers

Table 4.1: Related capacities used in the model

	Capacity Values (kg)
Treatment Facilities (Handling Capacity	6,000,000
Subsidized Junk Yard (Sorting Capacity)	1,300,000
Distributor Collection Point (Holding Capacity)	25,000
Municipality Collection Point (Holding Capacity)	2,000,000

household appliances, cooling and freezing appliances, TV's (monitors) and small household appliances. Estimated populations of next 6 years and total estimated amount waste for 4 types of WEEE are shared in Appendix A.

In this study, subsidized junkyards, treatment facilities and collection points do not hold inventory of the wastes or materials. However, handling/sorting capacities are defined for facilities/subsidized junkyards. Also, a collection center have a storage capacity for each time period. It is assumed that all treatment facilities, subsidized junk yards, municipality collection points and distributor collection points are identical in capacities. Related values are indicated in Table 4.1

Recoverable materials/components are ferro metals, aluminum, copper, plastic, glass, circuit boards. They are separated by utilizing required tools. Separated content are deposited and sold to the secondary market. Selling prices indicated in Table 4.2 are defined actual values in the market.

Table 4.2: Selling prices of the content inside WEEE

Content	Selling Price (TL/kg)
Ferrous Metals	1,12
Aluminum	6,9
Copper	22
Plastic	1,5
Glass	0,9
Circuit Board	22

Table 4.3: The ratios of recoverable materials inside products, adapted from [2]

	Recoverable materials inside WEEE					
Product Types	Ferrous Metals	Aluminum	Copper	Plastic	Glass	Circuit Board
Large Household Appliances	45.75	1.05	2.16	26.02	0	0.11
Cooling and Freezing Appliances	37.98	0.75	2.55	33.71	0	0
TV's (Monitors)	7.76	0.24	1.2	12.88	51.44	6.48
Small Household Appliances	20.5	2.5	4.5	22	0	0.5

All the materials in the wastes are not fully recyclable due to the quality issues. The minimum are recycling rates are taken from [2] and the ratio that the recoverable material inside four types of WEEE (q_{pm}) are calculated as shown in Table 4.3.

Emission values of transportation, disposal and contraction activities are adapted from [56]. CO_2 emitted to transport for one kg of waste per km is 0.00004 grams while disposal emission values are between 0.375 to 0.495 grams with respect to waste or material. CO_2 emitted to build a facility is $2,350,000$ grams.

4.2 Computational Results and Discussion

4.2.1 Solutions with Single Objectives

The model is solved for each objective separately first. In this section, the results of separate solutions will be presented.

Profit-oriented solution

This instance proves the potential that WEEE has remarkable amount of material inside to turn into raw material via recycling industry. The most dominant cost components are disposal, handling and sorting costs as shown in figure 4.7.

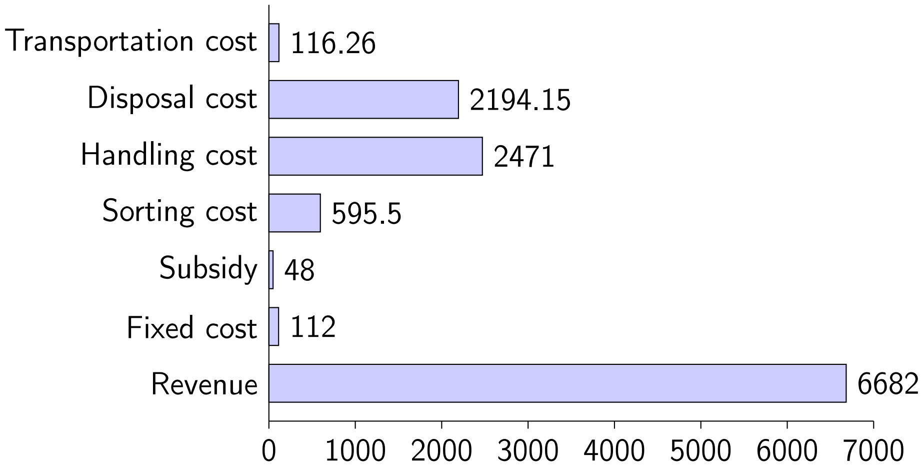

Figure 4.7: Fragmentation of first objective function (x10^5 TL)

In this solution, 14 out of 18 WEEE facilities are opened and 24 out of 40 junk yards are subsidized as illustrated in Figure 4.8. Dark blue and light blue nodes represent opened and unopened facilities while dark green and light green nodes represent subsidized and unsubsidized facilities. The second and third objective function values are also calculated as illustrated in Figure 4.9 and 4.10 respectively. The optimal value of the first objective function is 114,500,060.3 TL. Based on the optimal solution, the total emission value is 86,37 tons while 800 people are employed.

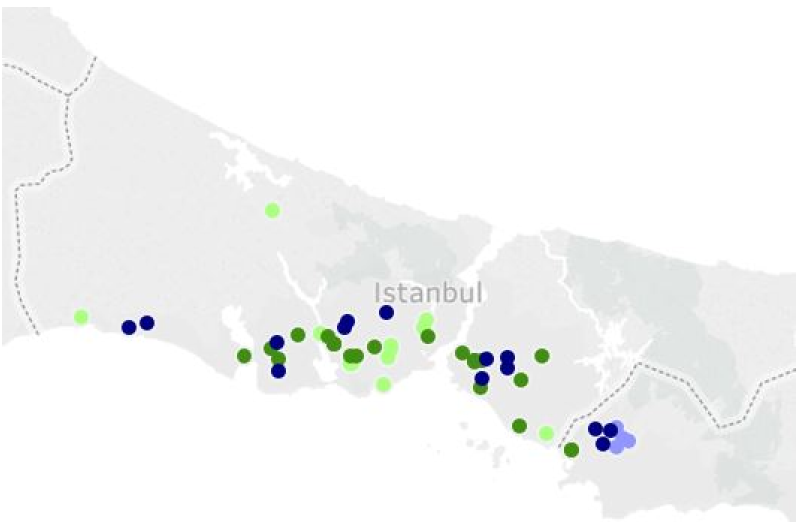

Figure 4.8: Opened facilities and subsidized junk yards in profit oriented solution

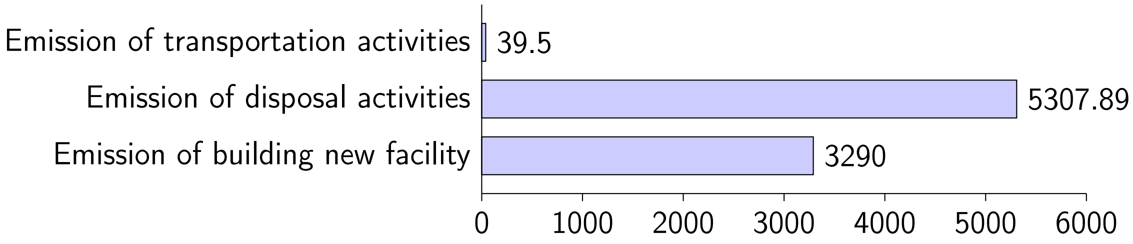

Figure 4.9: Fragmentation of second objective function (x10 kg)

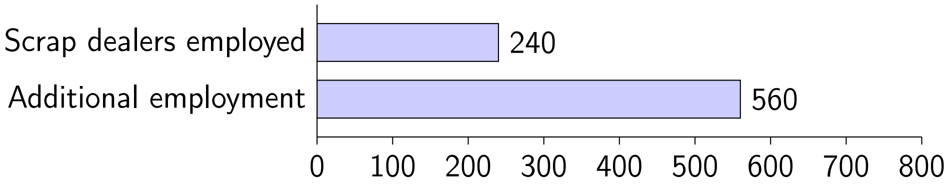

Figure 4.10: Fragmentation of third objective function

Emission-oriented solution

14 out of 18 WEEE facilities are opened and 28 out of 40 junk yards are subsidized considering the purpose of minimizing total CO_2 emission. Dark blue and light blue nodes represent opened and unopened facilities while dark green and light green nodes represent subsidized and unsubsidized facilities in Figure 4.12. The value of second objective function is 86,34 tons. The distribution of the second objective function is illustrated in Figure 4.11. Disposal activities have more harmful effect on environment than transportation and construction.

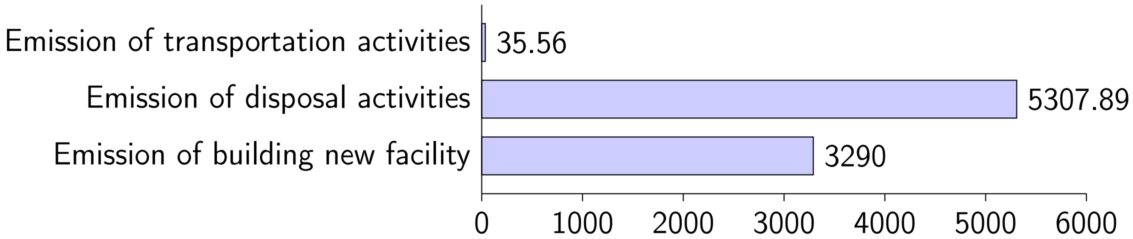

Figure 4.11: Fragmentation of the second objective function (x10 kg)

Based on the optimal solution of the second objective, the total profit is 75,531,411.46 TL while 840 people are employed in total. Thus, total revenue gained is much lower than previous instance even though employment is slightly higher (Figure 4.13 and 4.14).

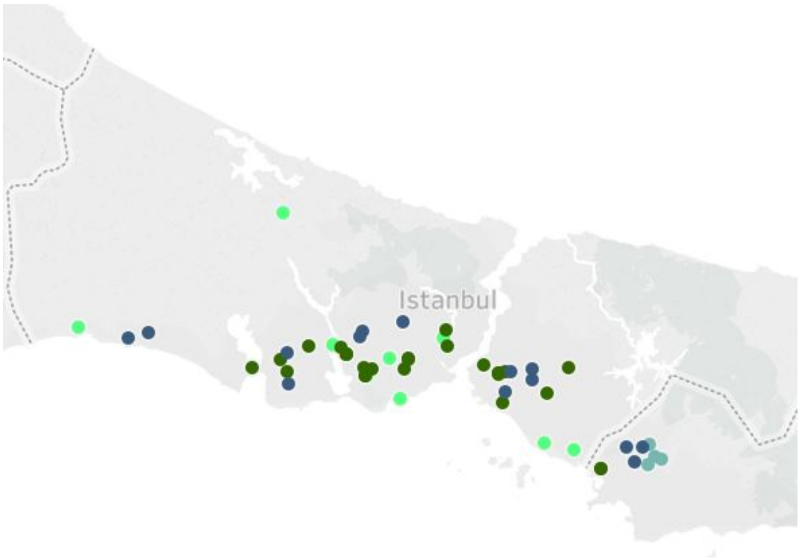

Figure 4.12: Opened facilities and subsidized junk yards in emission oriented solution

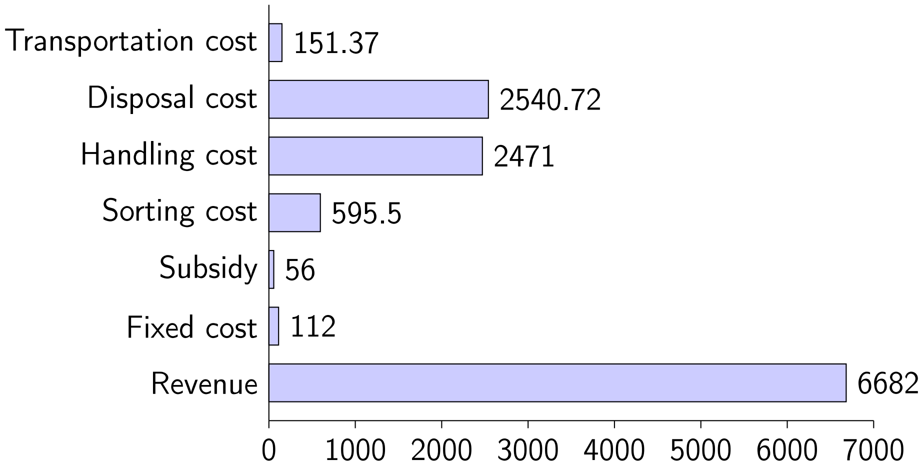

Figure 4.13: Fragmentation of the first objective function (x10^5 TL)

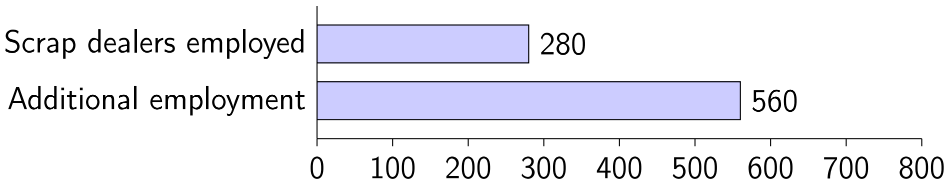

Figure 4.14: Fragmentation of the third objective function

Employment oriented solution

This instance considers only the number of people to be employed. The value of the third objective function is 1020 (Figure 4.15) under the decision of that all WEEE facilities are opened and 30 out of 40 junk yards are subsidized.

Opened facilities, subsidized and unsubsidized scrap yards are visualized as dark blue, dark green and light green nodes in Figure 4.16 respectively. Nevertheless, this instance does not make profit, the corresponding value of the first objective for this instance is -54,821,453.97 TL. In other words, revenue is not enough to cover expenses of the system as shown is Figure 4.17. This solution causes 97.55 tons CO_2 emission in total.

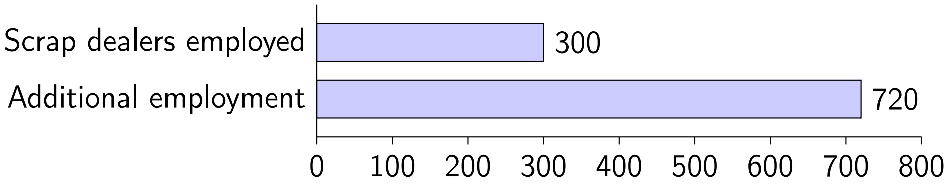

Figure 4.15: Fragmentation of the third objective function

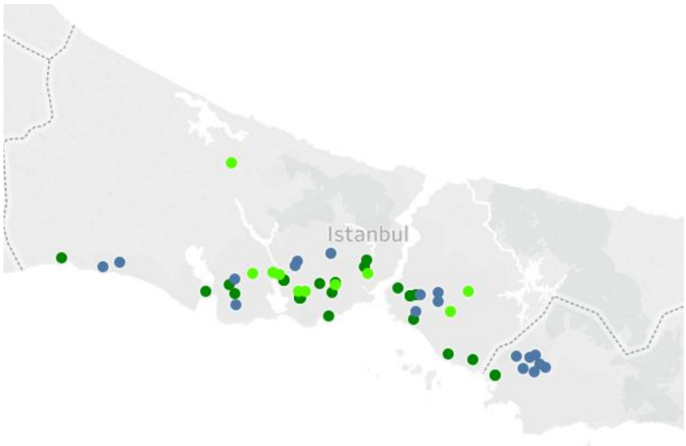

Figure 4.16: Opened facilities and subsidized junk yards in employment oriented solution

4.2.2 Pareto Optimal Solutions

As can be understood from individual solutions in the previous section, the objective functions conflict with each other. Thus, it is not possible to come up with an optimal solution considering three objectives at the same time. In this section, Pareto optimal solutions will be presented. The procedure for finding Pareto optimal solutions starts with finding a set of feasible solutions in the beginning. Thus, according to the results shared in the previous section, lower or upper bound values for each objective function were determined according to the characteristic of the objective function. More specifically, each objective function becomes the

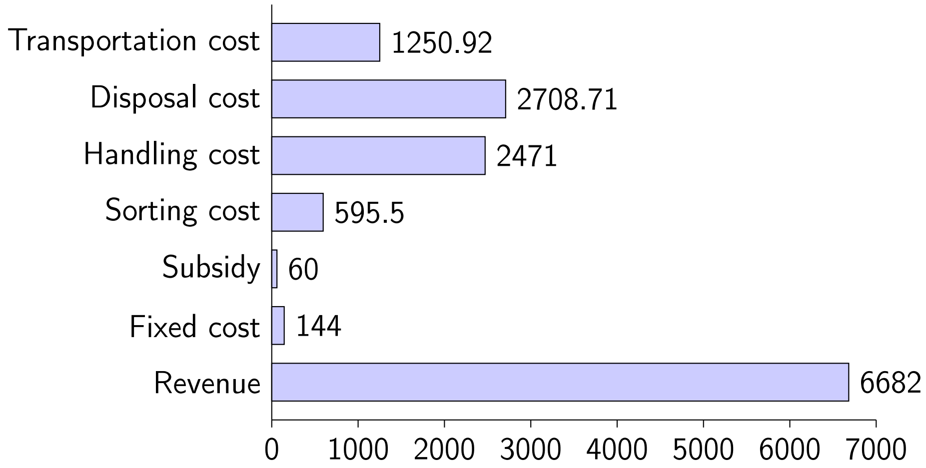

Figure 4.17: Fragmentation of the first objective function (x10^5 TL)

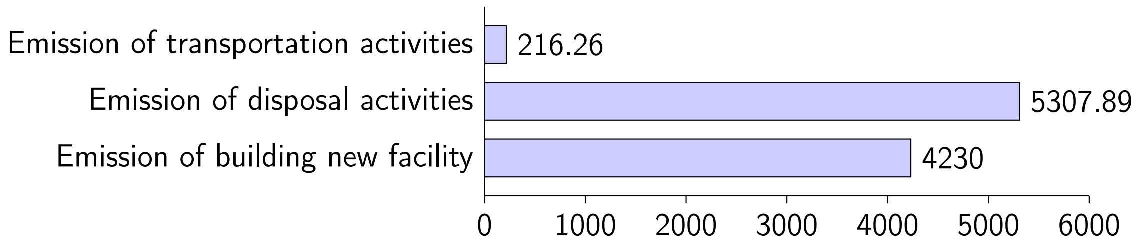

Figure 4.18: Fragmentation of the second objective function (x10 kg)

main objective function, respectively. All combinations of previously defined lower and upper values are added to the model as constraints. A total of 110 different scenarios were created according to these limits and the model was solved for all scenarios. The optimal solutions of the instances are visualized in Figure 4.19 and Figure 4.20 from different angles (see appendix for all solutions A.6).

The solutions shown in Figure 4.19 or 4.20 contain the solutions dominated by the other ones. Thus, the non-dominated set is found by pairwise comparisons of the solutions. For a solution to be able to dominate another solution, it is required that it must have better values in all objective functions. In other words, when all the solutions that are dominated by at least one other solution are eliminated, any pair of the remaining solutions will not be superior to each other. After comparisons, we have 34 non-dominated solutions (see Table A.7 in appendix). In this solution set, profit values vary to 90 millions to 114,5 millions while the smallest value of emission is 86.33 tons and the largest one is 95.75 tons. Employment values are discrete and 800, 810, 820, 840, 860, 920, 940, 950, 960, 980, 1020. For detailed presentation, the solution set is divided into three separate figures (see Figures 4.21, 4.22 and 4.23).

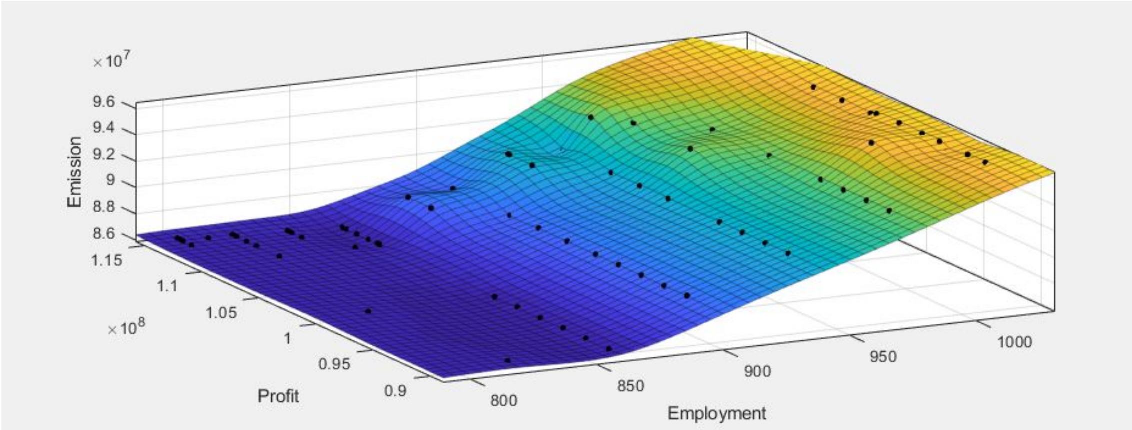

Figure 4.19: Set of optimal solutions - 1

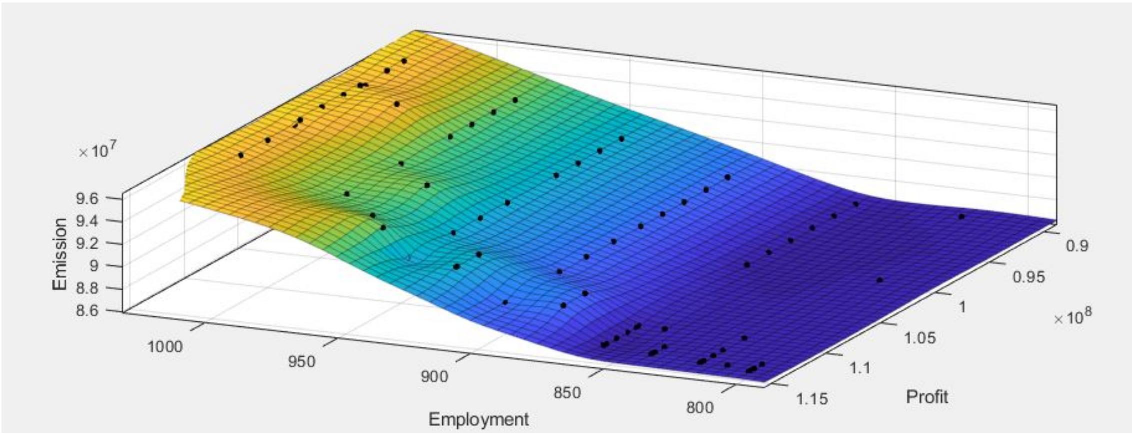

Figure 4.20: Set of optimal solutions - 2

In Figure 4.22, there is no clear pattern due to lack of more solution. However, if we examine the first and third tables together, it can be said that at different levels of employment, there is a similar pattern in emission and profit values.

4.3 Sensitivity Analysis

In this section, two dimensional Pareto frontiers for each pairwise of objective function are supplied to comprehend the relationship between them clearly.

Relationship between the first and second objective function

It can be realized that the better the greater value of the first objective function, the better the smaller value of the second objective function. Pareto frontier for this pair can be seen in Figure 4.24. It is clear that even though the second objective function is compromised, the rate of increase in revenue decreases.

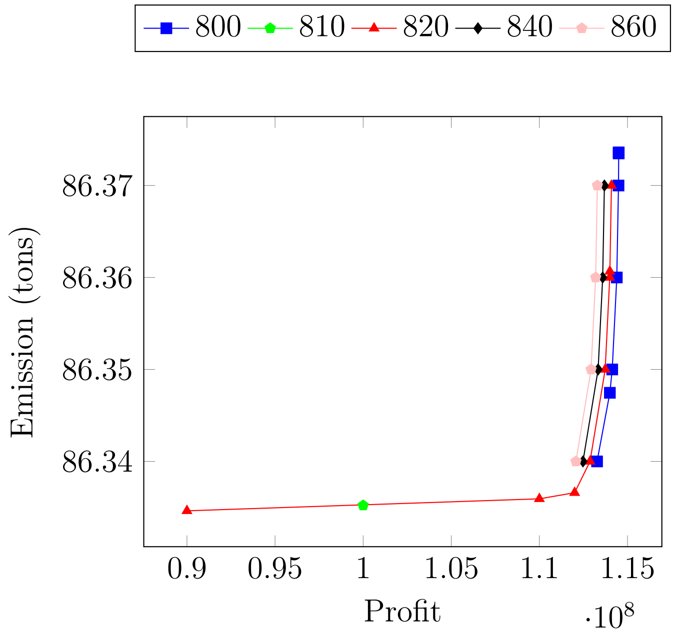

Figure 4.21: Non-dominated solutions - 1

In order to understand the differences between solutions, the components of the objective functions are investigated. It is recognized that total disposal, handling, sorting, new facility opening costs, subsidy and revenue values are same for all Pareto solutions. Similarly, emission of disposal and new facility opening is also same (see appendix for Table A.8). Thus, the transportation cost and corresponding emission values are conflicting with each other. Opened facilities are same while the subsidized junk yards change even the number of subsidized junkyards does not change.

Relationship between the first and third objective function

The blue dots in Figure 4.25 show all Pareto solutions considering profit and employment and the red ones are non-dominated solutions. In order to increase employment, more facilities must be opened and/or more junk yards must be subsidized which cause decrease in profit as shown in Figure 4.26 which are constituted with only non-dominated solutions.

Total disposal, handling, sorting costs and revenues do not change for the Pareto solutions. Overall disposal cost 219,414,209.9 TL, handling cost 247,101,708.6 TL and sorting cost 59,549,731.22 TL and the revenue is 668,191,440.5 TL. As can be seen the Table A.9 (see appendix), there is a trade of between transportation cost, fixed cost, subsidy and employment. When we compare the Pareto solutions two by two, it is realized that the transportation costs can increase when fewer

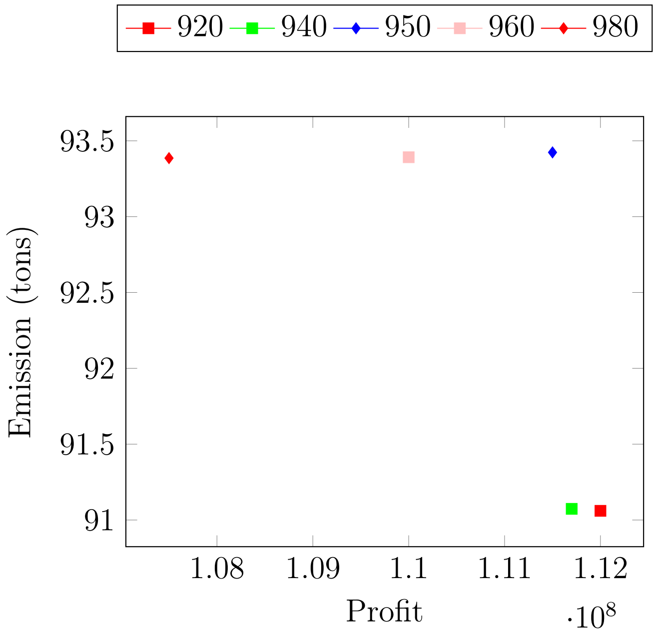

Figure 4.22: Non-dominated solutions - 2

treatment facilities were opened or fewer scrap yards were subsidized. The increase in transportation cost does not affect the reduction in total cost .

Relationship between the second and third objective function

As can be seen from Figure 4.27, the blue crosses show Pareto feasible solutions while the red circles are non-dominated solutions. As indicated before, the required number of worker for each facility is 40 and the number of scrap dealer working in each scrap yard is 10 people. For this reason, Figure 4.27 resembles a stair.

Similar reasoning mentioned in the previous case is still valid for this one. Even if opened facilities and subsidized junk yards denotes new job opportunities, emission values are affected by employment indirectly. As can be seen the Table A.10 (see appendix), there is a trade of between emission values of transportation and opening new facilities and employment. Total emission value for disposal activities does not change for the Pareto solutions and it is 53,07 tons for 6 years. Moreover, the number of employed scrap dealers is 300 people. Employment increases when new facility is opened, and the corresponding emission values also increase as expected. Transportation emissions for each Pareto solutions is approximately 0.4% of overall emission values. Transportation emissions do not have a dominant influence on the solutions.

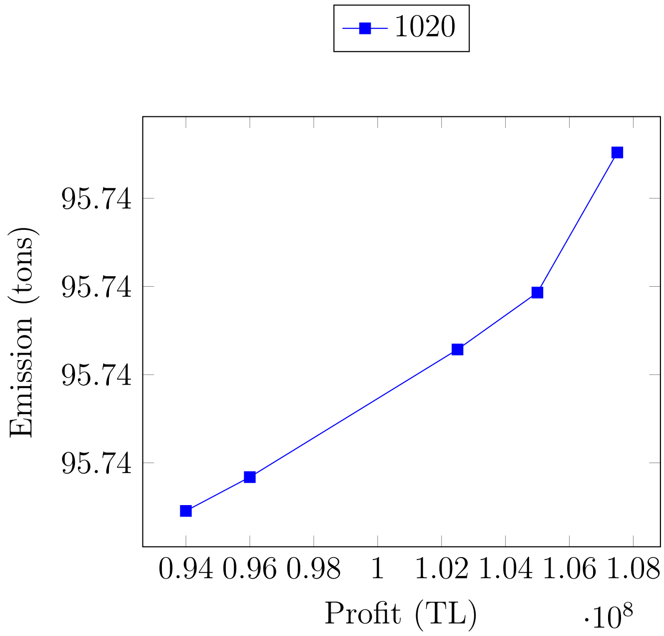

Figure 4.23: Non-dominated solutions - 3

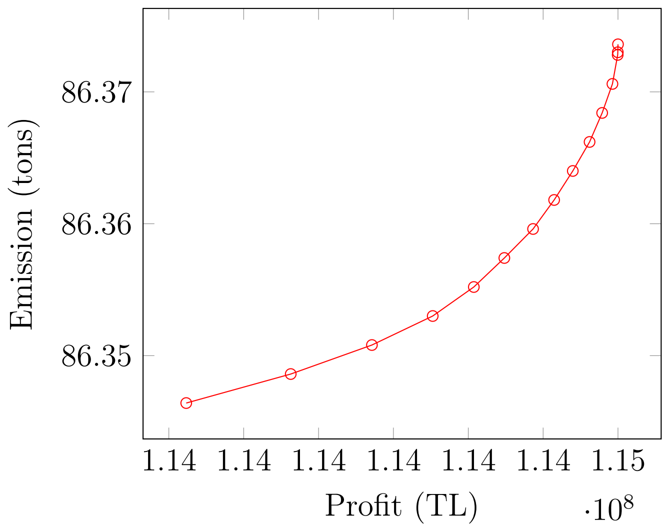

Figure 4.24: The Pareto frontier for the first and second objective

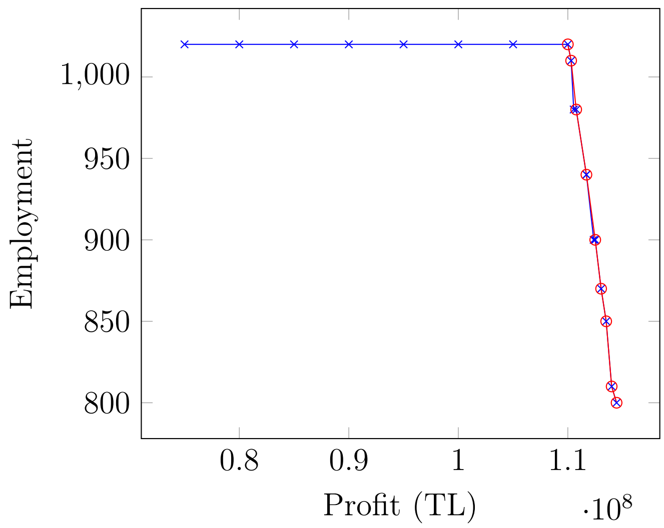

Figure 4.25: The Pareto solutions for the first and third objective

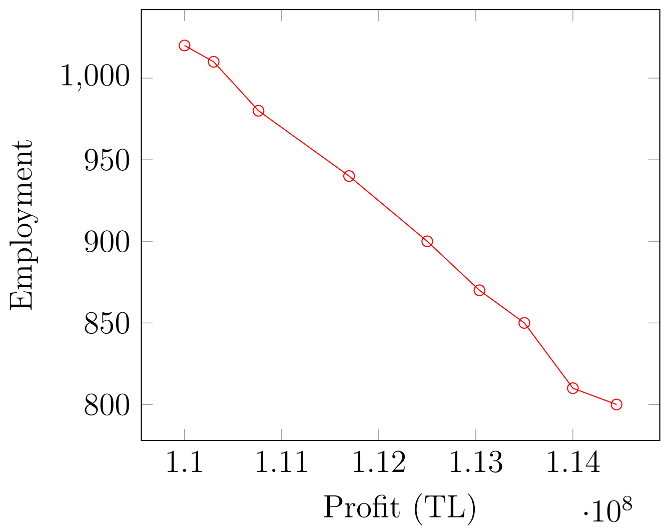

Figure 4.26: The Pareto frontier for the first and third objective

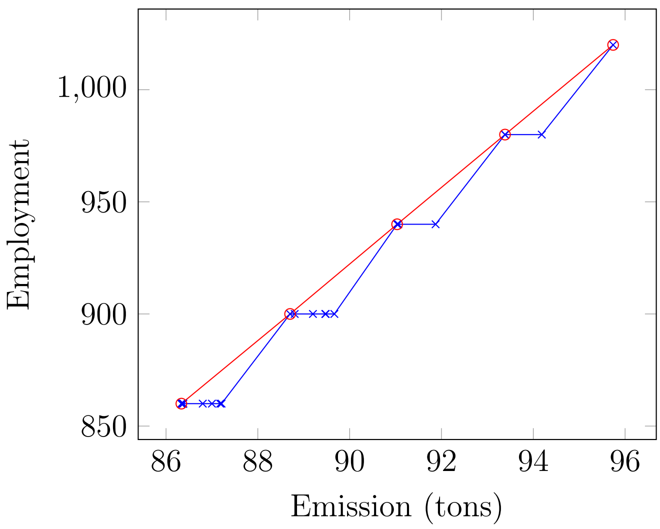

Figure 4.27: The Pareto frontier for the second and third objective

Chapter 5

Conclusion and Future Work

In this thesis study, a realistic RLND problem for WEEE has been modeled and implemented to the most crowded city of Turkey, Istanbul. The thesis answers questions regarding the locations of WEEE treatment facilities to be opened and WEEE junk yards to be subsidized and the flows between entities of designed RL network. Various outputs and goals are achieved in this thesis study. First, a deterministic multi objective MILP model is developed and implemented. Contribution of this study is to include illegal scrap dealers inside WEEE network and develop corresponding mathematical model. The population growth rate and waste collection target per capita is estimated and remaining data is collected from other RLND studies and professionals in recycling sector. The model is firstly implemented for profit-oriented, emission-oriented and employment-oriented objective functions separately. In order to investigate the balance among three objective functions, Pareto optimal solution set for multiple objectives is achieved and then non-dominated solutions are provided. In addition to Pareto optimal solutions, pairwise Pareto solutions are also obtained as sensitivity analysis. Since a major part of the data are real values, this study provides realistic and rational results.

This thesis study can be improved in several ways. First of all, it is assumed that the waste is occurred in waste generation points which is center of districts. This means that waste collection activities and corresponding cost, emission and employment issues are not considered in the proposed model. Especially for this study, the defined objective functions can be developed by taking collection activities into account.

Another improvement can be made for parameters. It is assumed that all parameters are deterministic. However, uncertainty is inevitable to model problems in more realistic way. In this study, the population and amount of waste generated in districts are estimated. The model can be developed by considering the generated waste as stochastic component.

Similar to the previous suggestion, the selling prices may vary in time. As can be understood from this study, the overall network has potential to make remarkable profit. The selling prices can be defined as fuzzy or stochastic parameter to evaluate the performance of the system.

Different quality levels for materials inside WEEE are not considered in this study. In other words, all recyclable materials are assumed as in same condition. The quality level dimension can be added to model to obtain more detailed analysis.

The computational time for some instances of the model solved for Pareto feasible set is approximately 50 hours. This problem can be solved in longer times for larger data set. Heuristics can be developed to reduce running time.

Appendix A

Some Appendix

Table A.1: Estimated population for between 2018-2023

	Population through years					
District/Years	2018	2019	2020	2021	2022	2023
Adalar	14,478	14,623	14,770	14,918	15,068	15,219
Arnavutköy	247,507	249,983	252,482	255,007	257,558	260,134
Ataşehir	422,513	426,739	431,006	435,317	439,671	444,068
Avcılar	430,770	435,078	439,429	443,824	448,263	452,746
Bağcılar	751,510	759,026	766,616	774,283	782,026	789,847
Bahçelievler	598,097	604,078	610,119	616,221	622,384	628,608
Bakırköy	222,437	224,662	226,908	229,178	231,470	233,785
Başakşehir	369,810	373,509	377,244	381,017	384,828	388,677
Bayrampaşa	273,148	275,880	278,639	281,426	284,241	287,084
Beşiktaş	189,356	191,250	193,163	195,095	197,046	199,017
Beykoz	250,410	252,915	255,444	257,999	260,579	263,185
Beylikdüzü	297,420	300,395	303,399	306,433	309,498	312,593
Beyoğlu	238,762	241,150	243,562	245,998	248,458	250,943
Büyükçekmece	237,185	239,557	241,953	244,373	246,817	249,286
Çatalca	68,935	69,625	70,321	71,025	71,736	72,454
Çekmeköy	239,611	242,008	244,428	246,873	249,342	251,836
Esenler	457,231	461,804	466,422	471,087	475,798	480,556
Esenyurt	795,010	802,961	810,990	819,100	827,291	835,564

Eyüp	377,650	381,427	385,241	389,094	392,985	396,915
Fatih	417,285	421,458	425,673	429,930	434,230	438,573
Gaziosmanpaşa	499,766	504,764	509,812	514,911	520,061	525,262
Güngören	298,509	301,495	304,510	307,556	310,632	313,739
Kadıköy	452,302	456,826	461,394	466,008	470,669	475,376
Kağıthane	439,685	444,082	448,523	453,009	457,540	462,116
Kartal	459,298	463,891	468,530	473,216	477,949	482,729
Küçükçekmece	766,609	774,276	782,018	789,839	797,738	805,716
Maltepe	490,151	495,053	500,004	505,005	510,056	515,157
Pendik	691,681	698,598	705,584	712,640	719,767	726,965
Sancaktepe	377,047	380,818	384,626	388,473	392,358	396,282
Sarıyer	342,753	346,181	349,643	353,140	356,672	360,239
Silivri	170,523	172,229	173,951	175,691	177,448	179,223
Sultanbeyli	324,709	327,957	331,236	334,549	337,895	341,274
Sultangazi	525,090	530,341	535,645	541,002	546,413	551,878
Şile	34,241	34,584	34,930	35,280	35,633	35,990
Şişli	272,803	275,532	278,287	281,070	283,881	286,720
Tuzla	242,232	244,655	247,101	249,573	252,069	254,590
Ümraniye	694,158	701,100	708,111	715,193	722,345	729,569
Üsküdar	535,537	540,893	546,302	551,766	557,284	562,857
Zeytinburnu	287,897	290,776	293,684	296,621	299,588	302,584

Table A.2: Estimated amount of type 1 waste generated in each time period (tons)

District	2018	2019	2020	2021	2022	2023
Arnavutköy	168.30	191.24	214.61	238.43	262.71	287.45
Ataşehir	287.31	326.46	366.36	407.02	448.46	490.70
Avcılar	292.92	332.83	373.51	414.98	457.23	500.28
Bağcılar	511.03	580.65	651.62	723.95	797.67	872.78
Bahçelievler	406.71	462.12	518.60	576.17	634.83	694.61
Bakırköy	151.26	171.87	192.87	214.28	236.10	258.33
Başakşehir	251.47	285.73	320.66	356.25	392.52	429.49
Bayrampaşa	185.74	211.05	236.84	263.13	289.93	317.23
Beşiktaş	128.76	146.31	164.19	182.41	200.99	219.91
Beykoz	170.28	193.48	217.13	241.23	265.79	290.82
Beylikdüzü	202.25	229.80	257.89	286.51	315.69	345.42
Beyoğlu	162.36	184.48	207.03	230.01	253.43	277.29
Büyükçekmece	161.29	183.26	205.66	228.49	251.75	275.46
Çatalca	46.88	53.26	59.77	66.41	73.17	80.06
Çekmeköy	162.94	185.14	207.76	230.83	254.33	278.28
Esenler	310.92	353.28	396.46	440.47	485.31	531.01
Esenyurt	540.61	614.27	689.34	765.86	843.84	923.30
Eyüp	256.80	291.79	327.45	363.80	400.84	438.59
Fatih	283.75	322.42	361.82	401.98	442.91	484.62
Gaziosmanpaşa	339.84	386.14	433.34	481.44	530.46	580.41
Güngören	202.99	230.64	258.83	287.56	316.84	346.68
Kadıköy	307.57	349.47	392.18	435.72	480.08	525.29
Kağıthane	298.99	339.72	381.24	423.56	466.69	510.64
Kartal	312.32	354.88	398.25	442.46	487.51	533.42
Küçükçekmece	521.29	592.32	664.72	738.50	813.69	890.32
Maltepe	333.30	378.72	425.00	472.18	520.26	569.25
Pendik	470.34	534.43	599.75	666.32	734.16	803.30
Sancaktepe	256.39	291.33	326.93	363.22	400.21	437.89
Sarıyer	233.07	264.83	297.20	330.19	363.81	398.06

Silivri	115.96	131.76	147.86	164.27	181.00	198.04
Sultanbeyli	220.80	250.89	281.55	312.80	344.65	377.11
Sultangazi	357.06	405.71	455.30	505.84	557.34	609.83
Şile	23.28	26.46	29.69	32.99	36.35	39.77
Şişli	185.51	210.78	236.54	262.80	289.56	316.83
Tuzla	174.56	198.35	222.59	247.30	272.48	298.14
Ümraniye	472.03	536.34	601.89	668.71	736.79	806.17
Üsküdar	364.17	413.78	464.36	515.90	568.43	621.96
Zeytinburnu	195.77	222.44	249.63	277.34	305.58	334.36

Table A.3: Estimated amount of type 2 waste generated in each time period (tons)

District	2018	2019	2020	2021	2022	2023
Arnavutköy	321.76	365.60	69.75	455.83	502.24	549.53
Ataşehir	549.27	624.11	119.07	778.13	857.36	938.09
Avcılar	560.00	636.30	121.39	793.34	874.11	956.43
Bağcılar	976.96	1,110.08	211.78	1,384.03	1,524.95	1,668.55
Bahçelievler	777.53	883.46	168.55	1,101.50	1,213.65	1,327.93
Bakırköy	289.17	328.57	62.68	409.66	451.37	493.87
Başakşehir	480.75	546.26	104.21	681.07	750.41	821.08
Bayrampaşa	355.09	403.47	76.97	503.05	554.27	606.46
Beşiktaş	246.16	279.70	53.36	348.73	384.24	420.42
Beykoz	325.53	369.89	70.57	461.17	508.13	555.98
Beylikdüzü	386.65	439.33	83.81	547.75	603.52	660.35
Beyoğlu	310.39	352.68	67.28	439.72	484.49	530.12
Büyükçekmece	308.34	350.35	66.84	436.82	481.29	526.62
Çatalca	89.62	101.83	19.43	126.96	139.89	153.06
Çekmeköy	311.49	353.94	67.52	441.29	486.22	532.00
Esenler	594.40	675.39	128.85	842.07	927.81	1,015.17
Esenyurt	1,033.51	1,174.33	224.04	1,464.14	1,613.22	1,765.13
Eyüp	490.95	557.84	106.42	695.51	766.32	838.48
Fatih	542.47	616.38	117.59	768.50	846.75	926.49

Gaziosmanpaşa	649.70	738.22	140.84	920.40	1,014.12	1,109.62
Güngören	388.06	440.94	84.12	549.76	605.73	662.77
Kadıköy	587.99	668.11	127.46	832.99	917.80	1,004.23
Kağıthane	571.59	649.47	123.90	809.75	892.20	976.22
Kartal	597.09	678.44	129.43	845.87	932.00	1,019.77
Küçükçekmece	996.59	1,132.38	216.03	1,411.84	1,555.59	1,702.08
Maltepe	637.20	724.02	138.13	902.70	994.61	1,088.27
Pendik	899.19	1,021.70	194.92	1,273.84	1,403.55	1,535.71
Sancaktepe	490.16	556.95	106.25	694.40	765.10	837.15
Sarıyer	445.58	506.29	96.59	631.24	695.51	761.00
Silivri	221.68	251.88	48.05	314.05	346.02	378.61
Sultanbeyli	422.12	479.64	91.50	598.01	658.90	720.94
Sultangazi	682.62	775.62	147.97	967.04	1,065.51	1,165.84
Şile	44.51	50.58	9.65	63.06	69.48	76.03
Şişli	354.64	402.97	76.88	502.41	553.57	605.70
Tuzla	333.72	336.29	318.98	341.57	344.28	347.05
Ümraniye	902.41	1,025.36	195.62	1,278.41	1,408.57	1,541.21
Üsküdar	696.20	791.06	150.92	986.28	1,086.70	1,189.04
Zeytinburnu	374.27	425.26	81.13	530.21	584.20	639.21

Table A.4: Estimated amount of type 3 waste generated in each time period (tons)

District	2018	2019	2020	2021	2022	2023
Arnavutköy	212.86	241.86	271.42	301.55	332.25	363.54
Ataşehir	363.36	412.87	463.33	514.76	567.18	620.59
Avcılar	370.46	420.94	472.39	524.82	578.26	632.71
Bağcılar	646.30	734.36	824.11	915.59	1,008.81	1,103.81
Bahçelievler	514.36	584.45	655.88	728.68	802.88	878.48
Bakırköy	191.30	217.36	243.93	271.00	298.60	326.71
Başakşehir	318.04	361.37	405.54	450.55	496.43	543.18
Bayrampaşa	234.91	266.91	299.54	332.79	366.67	401.20
Beşiktaş	162.85	185.03	207.65	230.70	254.19	278.13

Beykoz	215.35	244.70	274.60	305.08	336.15	367.80
Beylikdüzü	255.78	290.63	326.15	362.36	399.25	436.85
Beyoğlu	205.34	233.31	261.83	290.89	320.51	350.69
Büyükçekmece	203.98	231.77	260.10	288.97	318.39	348.38
Çatalca	59.28	67.36	75.60	83.99	92.54	101.25
Çekmeköy	206.07	234.14	262.76	291.93	321.65	351.94
Esenler	393.22	446.80	501.40	557.06	613.78	671.58
Esenyurt	683.71	776.86	871.81	968.59	1,067.21	1,167.70
Eyüp	324.78	369.03	414.13	460.10	506.95	554.69
Fatih	358.87	407.76	457.60	508.39	560.16	612.91
Gaziosmanpaşa	429.80	488.36	548.05	608.88	670.88	734.05
Güngören	256.72	291.70	327.35	363.68	400.72	438.45
Kadıköy	388.98	441.98	496.00	551.05	607.16	664.34
Kağıthane	378.13	429.65	482.16	535.68	590.23	645.81
Kartal	395.00	448.81	503.67	559.58	616.55	674.61
Küçükçekmece	659.28	749.11	840.67	933.98	1,029.08	1,125.99
Maltepe	421.53	478.96	537.50	597.17	657.97	719.93
Pendik	594.85	675.89	758.50	842.70	928.50	1,015.93
Sancaktepe	324.26	368.44	413.47	459.37	506.14	553.80
Sarıyer	294.77	334.93	375.87	417.59	460.11	503.43
Silivri	146.65	166.63	187.00	207.75	228.91	250.46
Sultanbeyli	279.25	317.30	356.08	395.60	435.88	476.93
Sultangazi	451.58	513.10	575.82	639.73	704.87	771.25
Şile	29.45	33.46	37.55	41.72	45.97	50.30
Şişli	234.61	266.58	299.16	332.37	366.21	400.69
Tuzla	220.77	222.47	224.20	225.96	227.76	229.59
Ümraniye	596.98	678.31	761.22	845.72	931.83	1,019.57
Üsküdar	460.56	523.31	587.27	652.46	718.90	786.59
Zeytinburnu	247.59	281.33	315.71	350.75	386.47	422.86

Table A.5: Estimated amount of type 4 waste generated in each time period (tons)

District	2018	2019	2020	2021	2022	2023
Arnavutköy	158.40	179.99	201.99	224.41	247.26	270.54
Ataşehir	270.41	307.25	344.80	383.08	422.08	461.83
Avcılar	275.69	313.26	351.54	390.57	430.33	470.86
Bağcılar	480.97	546.50	613.29	681.37	750.74	821.44
Bahçelievler	382.78	434.94	488.10	542.27	597.49	653.75
Bakırköy	142.36	161.76	181.53	201.68	222.21	243.14
Başakşehir	236.68	268.93	301.80	335.29	369.43	404.22
Bayrampaşa	174.81	198.63	222.91	247.65	272.87	298.57
Beşiktaş	121.19	137.70	154.53	171.68	189.16	206.98
Beykoz	160.26	182.10	204.36	227.04	250.16	273.71
Beylikdüzü	190.35	216.28	242.72	269.66	297.12	325.10
Beyoğlu	152.81	173.63	194.85	216.48	238.52	260.98
Büyükçekmece	151.80	172.48	193.56	215.05	236.94	259.26
Çatalca	44.12	50.13	56.26	62.50	68.87	75.35
Çekmeköy	153.35	174.25	195.54	217.25	239.37	261.91
Esenler	292.63	332.50	373.14	414.56	456.77	499.78
Esenyurt	508.81	578.13	648.79	720.81	794.20	868.99
Eyüp	241.70	274.63	308.19	342.40	377.27	412.79
Fatih	267.06	303.45	340.54	378.34	416.86	456.12
Gaziosmanpaşa	319.85	363.43	407.85	453.12	499.26	546.27
Güngören	191.05	217.08	243.61	270.65	298.21	326.29
Kadıköy	289.47	328.91	369.12	410.09	451.84	494.39
Kağıthane	281.40	319.74	358.82	398.65	439.24	480.60
Kartal	293.95	334.00	374.82	416.43	458.83	502.04
Küçükçekmece	490.63	557.48	625.61	695.06	765.83	837.94
Maltepe	313.70	356.44	400.00	444.40	489.65	535.76
Pendik	442.68	502.99	564.47	627.12	690.98	756.04
Sancaktepe	241.31	274.19	307.70	341.86	376.66	412.13
Sarıyer	219.36	249.25	279.71	310.76	342.41	374.65

Silivri	109.13	124.00	139.16	154.61	170.35	186.39
Sultanbeyli	207.81	236.13	264.99	294.40	324.38	354.92
Sultangazi	336.06	381.85	428.52	476.08	524.56	573.95
Şile	21.91	24.90	27.94	31.05	34.21	37.43
Şişli	174.59	198.38	222.63	247.34	272.53	298.19
Tuzla	164.29	165.56	166.84	168.16	169.49	170.86
Ümraniye	444.26	504.79	566.49	629.37	693.45	758.75
Üsküdar	342.74	389.44	437.04	485.55	534.99	585.37
Zeytinburnu	184.25	209.36	234.95	261.03	287.60	314.69

Table A.6: Set of optimal solutions

Solution number	Profit (TL)	Emission (Tons)	Employment
1	114,500,060.33	86.3736	800
2	114,500,060.33	86.3735	800
3	114,500,008.77	86.3700	800
4	114,489,283.48	86.3600	800
5	114,392,276.65	86.3500	800
6	114,132,935.10	86.3737	800
7	114,000,000.00	86.3737	800
8	113,273,129.51	86.3740	800
9	114,000,000.00	86.3700	810
10	100,000,000.00	86.3607	810
11	114,100,200.51	86.3594	820
12	114,100,200.51	86.3475	820
13	114,097,342.46	86.3600	820
14	114,088,928.75	86.3500	820
15	114,000,000.00	86.3737	820
16	113,992,278.99	86.3737	820
17	113,732,944.29	86.3737	820
18	112,873,129.51	86.3700	820
19	112,000,000.00	86.3600	820

20	110,000,000.00	86.3500	820
21	90,000,000.00	86.3737	820
22	113,700,200.51	86.3700	840
23	113,700,200.51	86.3400	840
24	113,700,200.51	86.3600	840
25	113,689,436.38	86.3500	840
26	113,592,278.99	86.3400	840
27	113,332,935.10	88.7237	840
28	112,473,129.51	88.7237	840
29	110,000,000.00	88.7237	850
30	113,300,200.51	86.3400	860
31	113,300,200.51	91.0737	860
32	113,300,200.51	91.0737	860
33	113,289,440.99	86.3400	860
34	113,192,276.65	86.3396	860
35	112,932,944.29	86.3366	860
36	112,073,129.51	91.0606	860
37	112,000,000.00	86.3396	860
38	112,000,000.00	88.6945	860
39	111,022,134.75	91.0737	860
40	110,258,970.32	93.4237	860
41	110,000,000.00	86.3378	860
42	110,000,000.00	86.3500	860
43	110,000,000.00	86.3359	860
44	100,000,000.00	86.3360	860
45	100,000,000.00	88.6861	860
46	100,000,000.00	903701.	860
47	100,000,000.00	93.3918	860
48	100,000,000.00	86.3600	860
49	98,000,000.00	86.3368	860
50	96,000,000.00	86.3377	860
51	94,000,000.00	93.3859	860

52	92,000,000.00	95.7427	860
53	90,000,000.00	88.6861	860
54	90,000,000.00	91.0359	860
55	90,000,000.00	88.6916	860
56	90,000,000.00	91.0356	860
57	90,000,000.00	93.3857	860
58	90,000,000.00	95.7419	860
59	112,000,000.00	95.7416	880
60	110,000,000.00	88.6913	880
61	112,500,200.51	91.0414	900
62	112,500,200.51	93.3915	900
63	112,500,200.51	95.9205	900
64	107,500,000.00	86.3600	900
65	105,000,000.00	86.3357	900
66	102,500,000.00	86.3370	900
67	100,000,000.00	86.3352	900
68	100,000,000.00	86.3356	900
69	98,000,000.00	86.3353	900
70	98,000,000.00	88.6853	900
71	96,000,000.00	96.0000	900
72	96,000,000.00	88.6910	900
73	94,000,000.00	88.6909	900
74	94,000,000.00	95.7352	900
75	92,000,000.00	93.3852	900
76	92,000,000.00	86.3700	900
77	112,100,200.51	91.0352	920
78	112,100,200.51	88.6934	920
79	112,000,000.00	95.9995	920
80	110,000,000.00	96.0000	920
81	111,700,200.51	88.6850	940
82	107,500,000.00	91.0350	940
83	105,000,000.00	86.3353	940

84	102,500,000.00	93.3851	940
85	98,000,000.00	95.7409	940
86	96,000,000.00	88.6933	940
87	94,000,000.00	93.3850	940
88	92,000,000.00	95.9907	940
89	92,000,000.00	88.6886	940
90	111,500,200.51	88.6905	950
91	110,000,000.00	86.3700	960
92	105,000,000.00	91.0349	960
93	107,500,000.00	95.7407	980
94	102,500,000.00	96.0000	980
95	98,000,000.00	86.3700	980
96	96,000,000.00	88.6903	980
97	94,000,000.00	91.0348	980
98	92,000,000.00	91.0404	980
99	98,000,000.00	93.3848	1000
100	107,500,000.00	88.7386	1020
101	105,000,000.00	86.3349	1020
102	102,500,000.00	86.3355	1020
103	102,003,024.06	86.3346	1020
104	100,000,000.00	86.3347	1020
105	98,000,000.00	86.3352	1020
106	96,474,568.88	86.3361	1020
107	96,000,000.00	86.3346	1020
108	94,000,000.00	86.3352	1020
109	94,000,000.00	86.3736	1020
110	92,455,074.19	86.3737	1020

Table A.7: Non-dominated solutions

Solution number	Profit (TL)	Emission (Tons)	Employment
1	114,500,060.33	86.3736	800
2	114,500,008.77	86.3735	800
3	114,489,283.48	86.3700	800
4	114,392,276.65	86.3600	800
5	114,132,935.10	86.3500	800
6	114,000,000.00	86.3475	800
7	113,273,129.51	86.3400	800
8	100,000,000.00	86.3352	810
9	114,088,928.75	86.3700	820
10	114,000,000.00	86.3607	820
11	113,992,278.99	86.3600	820
12	113,732,944.29	86.3500	820
13	112,873,129.51	86.3400	820
14	112,000,000.00	86.3366	820
15	110,000,000.00	86.3359	820
16	90,000,000.00	86.3346	820
17	113,689,436.38	86.3700	840
18	113,592,278.99	86.3600	840
19	113,332,935.10	86.3500	840
20	112,473,129.51	86.3400	840
21	113,289,440.99	86.3700	860
22	113,192,276.65	86.3600	860
23	112,932,944.29	86.3500	860
24	112,073,129.51	86.3400	860
25	112,000,000.00	91.0606	920
26	111,700,200.51	91.0737	940
27	111,500,200.51	93.4237	950
28	110,000,000.00	93.3918	960
29	107,500,000.00	93.3859	980

30	107,500,000.00	95.7427	1,020
31	105,000,000.00	95.7419	1,020
32	102,500,000.00	95.7416	1,020
33	96,000,000.00	95.7409	1,020
34	94,000,000.00	95.7407	1,020

Table A.8: Relation between the first and second objective functions

Solution #	Transportation Cost (TL)	Emission of Transportation (g)	Subsidized Junkyards
1	11,625,730.421	394,737.126	2,4-7,9,10,13-18,20-23-30,33-36,38,39
2	11,625,984.521	394,134.713	2,4-7,9-21,23,30,33-36,38,39
3	11,626,125.782	393,934.713	2,4-7,9,10,13-21,23,30,33-36,38,39
4	11,633,140.566	391,734.713	2,4-7,9,10,13-21,23,30,33-36,38,39
5	11,646,872.901	389,534.713	2,4-7,9,10,13-20,23,25,30,33-36,38,39
6	11,663,677.757	387,334.713	2,4-7,10,13-20,23-25,30,33-36,38,39
7	11,686,106.548	385,134.713	2,4-7,10,13-20,23-25,30,33-36,38,39
8	11,711,023.392	382,934.713	2,4-7,10,13-20,23-25,30,33-36,38,39
9	11,739,180.387	380,734.713	2,4-7,10,13-20,23-25,30,33-36,38,39
10	11,777,534.027	378,534.713	2,4-7,9,10,13-20,24,25,30,33-36,38,39
11	11,818,325.511	376,334.713	2,4-7,10,13-20,23-25,30,33-36,38,39
12	11,873,231.810	374,134.713	2,4-7,10,13-20,24,25,30,33-36,38-40
13	11,954,453.809	371,934.713	2,4-7,10,13-20,23-25,30,33-36,38,39
14	12,202,512.532	367,534.713	2,4-7,10,13-20,24,25,30,33-36,38-40
15	12,465,734.551	364,134.713	2,4-7,10,13-20,23-25,30,33-36,38,39

Table A.9: Relation between the first and third objective functions

Sol. #	Transportation cost (TL)	Subsidy (TL)	Fixed cost (TL)	Employment for Treatment Facility	Employment of Scrap Dealer	Opened Facilities	Subsidized Junk Yards
1	11,725,790.76	6,000,000	14,400,000	720	300	Facilities	1,2,4-7,9-11,13-23,26, 27,30,33-39
2	11,625,583.25	5,800,000	14,400,000	720	290	All facilites	2,4-7,9,10,12-18,20-23, 25,27,30-36,38,39
3	11,763,560.3	6,000,000	13,600,000	680	300	All facilities except 12	2-10,12-20,23-25,28-30, 33-36,38,39
4	11,630,629.17	6,000,000	12,800,000	640	300	All facilities except 12,17	2-10,13-18,20,21,23,25-28, 30,31,33-36,38,39
5	11,625,639.41	6,000,000	12,000,000	600	300	All facilities except 4,12,17	1-10,13-18,20-23,25, 26,30,33-36,38-40
6	11,688,254.29	5,400,000	12,000,000	600	270	All facilities except 4,12,17	2-7,10,13-18,22,23,25, 26,28-30,33-36,38-40
7	11,625,658.3	5,800,000	11,200,000	560	290	All facilities except 4,12,14,17	2,4-7,9,10,12-18,20-23, 25,29,30,32-39
8	11,925,790.76	5,000,000	11,200,000	560	250	2,3,5-11,13,15-18	2,4,5,7,10,12-20,22,23, 25,29,30,33-36,38,39
9	11,675,790.76	4,800,000	11,200,000	560	240	2,3,5-13,15,16,18	2,4-7,9,10,13-18,20,21, 23,25,30,33-36,38,39

Table A.10: Relation between the second and third objective functions

Sol. #	Emission of Transportation (g)	Emission of Opening Facilities (g)	Employment for Treatment Facility	Employment of Scrap Dealer	Opened Facilities	Subsidized Junk Yards
1	355,548.44	32,900,000	560	300	1,2,4-11,13,15,16,18	2,4-10,13-20,23,25,28-36,38-40
2	373,589.47	35,250,000	600	300	1,2,4-13,15,16,18	2,4-8,10,12-21,24-27,30,32-36,38-40
3	355,349.60	37,600,000	640	300	All facilities except for 12,17	2,4-11,13-20,23,25,28,30-36,38-40
4	355,449.67	39,950,000	680	300	All facilities except for 3	2,4-11,13-20,23,26,28,30-36,38-40
5	360,639.69	42,300,000	720	300	All facilities	10-40

Bibliography

[1] F. O. Ongondo, I. D. Williams, and T. J. Cherrett, "How are weee doing? a global review of the management of electrical and electronic wastes," *Waste management*, vol. 31, no. 4, pp. 714–730, 2011.

[2] H. S. Kilic, U. Cebeci, and M. B. Ayhan, "Reverse logistics system design for the waste of electrical and electronic equipment (weee) in turkey," *Resources, Conservation and Recycling*, vol. 95, pp. 120–132, 2015.

[3] J. Huisman, M. Van der Maesen, R. Eijsbouts, F. Wang, C. Baldé, and C. Wielenga, "The dutch weee flows," *United Nations University, ISP–SCYCLE, Bonn, Germany*, vol. 15, 2012.

[4] L. M. Hilty and B. Aebischer, *ICT innovations for sustainability*, vol. 310. Springer, 2015.

[5] F. Wang, J. Huisman, A. Stevels, and C. P. Baldé, "Enhancing e-waste estimates: Improving data quality by multivariate input–output analysis," *Waste management*, vol. 33, no. 11, pp. 2397–2407, 2013.

[6] P. Manomaivibool, "Extended producer responsibility in a non-oecd context: The management of waste electrical and electronic equipment in india," *Resources, Conservation and Recycling*, vol. 53, no. 3, pp. 136–144, 2009.

[7] P. Sawhney, M. Henzler, S. Melnitzky, and A. Lung, "Best practices for e-waste management in developed countries," *Adelphi Research, Austria*, 2008.

[8] C. Achillas, C. Vlachokostas, D. Aidonis, N. Moussiopoulos, E. Iakovou, and G. Banias, "Optimising reverse logistics network to support policy-making in

the case of electrical and electronic equipment," *Waste Management*, vol. 30, no. 12, pp. 2592–2600, 2010.

[9] G. T. Temur and B. Bolat, "Evaluating efforts to build sustainable weee reverse logistics network design: comparison of regulatory and non-regulatory approaches," *International Journal of Sustainable Engineering*, vol. 10, no. 6, pp. 358–383, 2017.

[10] P. Shrivastava and S. Hart, "Creating sustainable corporations," *Business Strategy and the Environment*, vol. 4, no. 3, pp. 154–165, 1995.

[11] R. E. C. R. Turkey, "Regulatory impact assessment of eu waste electrical and electronic equipment (weee) directive (2002/96/ec)," 2012.

[12] K. Govindan, H. Soleimani, and D. Kannan, "Reverse logistics and closed-loop supply chain: A comprehensive review to explore the future," *European Journal of Operational Research*, vol. 240, no. 3, pp. 603–626, 2015.

[13] U. Lehtinen and K. Poikela, "Challenges of weee on reverse logistics: a case study on a collection network in finland," in *Proceedings of Logistics Research Network Annual Conference*, vol. 2006, pp. 6th–8th, 2006.

[14] M. A. Ilgin and S. M. Gupta, "Environmentally conscious manufacturing and product recovery (ecmpro): A review of the state of the art," *Journal of environmental management*, vol. 91, no. 3, pp. 563–591, 2010.

[15] S. K. Srivastava, "Network design for reverse logistics," *Omega*, vol. 36, no. 4, pp. 535–548, 2008.

[16] J. Guiltinan and N. Nwokoye, "Reverse channels for recycling: an analysis for alternatives and public policy implications," in *American Marketing Association Proceedings*, vol. 36, pp. 341–46, Spring and Fall, 1974.

[17] P. M. Ginter and J. M. Starling, "Reverse distribution channels for recycling," *California Management Review*, vol. 20, no. 3, pp. 72–82, 1978.

[18] P. R. Murphy and R. Poist, "Management of logistical retromovements: an empirical analysis of literature suggestions," in *Journal of the Transportation Research Forum*, vol. 29, 1988.

[19] A. Atabarut, "Value of quality information of returns in product recovery management," 2009.

[20] J. R. Stock, *Reverse logistics: White paper.* Council of Logistics Management, 1992.

[21] T. L. Pohlen and M. Theodore Farris, "Reverse logistics in plastics recycling," *International Journal of Physical Distribution & Logistics Management*, vol. 22, no. 7, pp. 35–47, 1992.

[22] R. Kopicki, M. J. Berg, and L. Legg, "Reuse and recycling-reverse logistics opportunities," 1993.

[23] D. S. Rogers and R. Tibben-Lembke, "An examination of reverse logistics practices," *Journal of business logistics*, vol. 22, no. 2, pp. 129–148, 2001.

[24] C. R. Carter and L. M. Ellram, "Reverse logistics: a review of the literature and framework for future investigation," *Journal of business logistics*, vol. 19, no. 1, p. 85, 1998.

[25] F. Melissen and A. De Ron, "Defining recovery practices-definitions and terminology," *International Journal on Environmentally Conscious Manufacturing and Design*, vol. 8, no. 2, pp. 1–18, 1999.

[26] C. Prahinski and C. Kocabasoglu, "Empirical research opportunities in reverse supply chains," *Omega*, vol. 34, no. 6, pp. 519–532, 2006.

[27] V. D. R. Guide, T. P. Harrison, and L. N. Van Wassenhove, "The challenge of closed-loop supply chains," *Interfaces*, vol. 33, no. 6, pp. 3–6, 2003.

[28] H. Winkler, "Closed-loop production systems—a sustainable supply chain approach," *CIRP Journal of Manufacturing Science and Technology*, vol. 4, no. 3, pp. 243–246, 2011.

[29] G. Easwaran and H. Üster, "A closed-loop supply chain network design problem with integrated forward and reverse channel decisions," *Iie Transactions*, vol. 42, no. 11, pp. 779–792, 2010.

[30] F. J. García-Rodríguez, C. Castilla-Gutiérrez, and C. Bustos-Flores, "Implementation of reverse logistics as a sustainable tool for raw material purchasing in developing countries: The case of venezuela," *International Journal of Production Economics*, vol. 141, no. 2, pp. 582–592, 2013.

[31] T. B. Gooley, "The who, what and where of reverse logistics," *Logistics Management and Distribution*, 2003.

[32] R. S. Tibben-Lembke, "Life after death: reverse logistics and the product life cycle," *International Journal of Physical Distribution & Logistics Management*, vol. 32, no. 3, pp. 223–244, 2002.

[33] J. R. Huscroft, B. T. Hazen, D. J. Hall, J. B. Skipper, and J. B. Hanna, "Reverse logistics: past research, current management issues, and future directions," *The International Journal of Logistics Management*, vol. 24, no. 3, pp. 304–327, 2013.

[34] T. Ye and Y. Zhenhua, "Reverse logistics network: A literature review," *Journal of Chemical and Pharmaceutical Research*, vol. 6, no. 7, pp. 1916–1921, 2014.

[35] K. Govindan, M. Fattahi, and E. Keyvanshokooh, "Supply chain network design under uncertainty: A comprehensive review and future research directions," *European Journal of Operational Research*, vol. 263, no. 1, pp. 108–141, 2017.

[36] G. C. Souza, "Closed-loop supply chains: a critical review, and future research," *Decision Sciences*, vol. 44, no. 1, pp. 7–38, 2013.

[37] S. Agrawal, R. K. Singh, and Q. Murtaza, "A literature review and perspectives in reverse logistics," *Resources, Conservation and Recycling*, vol. 97, pp. 76–92, 2015.

[38] E. Bazan, M. Y. Jaber, and S. Zanoni, "A review of mathematical inventory models for reverse logistics and the future of its modeling: An environmental perspective," *Applied Mathematical Modelling*, vol. 40, no. 5-6, pp. 4151–4178, 2016.

[39] K. Govindan, P. Paam, and A.-R. Abtahi, “A fuzzy multi-objective optimization model for sustainable reverse logistics network design,” *Ecological indicators*, vol. 67, pp. 753–768, 2016.

[40] A. Alshamsi and A. Diabat, “A reverse logistics network design,” *Journal of Manufacturing Systems*, vol. 37, pp. 589–598, 2015.

[41] B. Ayvaz, B. Bolat, and N. Aydın, “Stochastic reverse logistics network design for waste of electrical and electronic equipment,” *Resources, conservation and recycling*, vol. 104, pp. 391–404, 2015.

[42] D. Kannan, A. Diabat, M. Alrefaei, K. Govindan, and G. Yong, “A carbon footprint based reverse logistics network design model,” *Resources, conservation and recycling*, vol. 67, pp. 75–79, 2012.

[43] D. Millet *et al.*, “Designing a sustainable reverse logistics channel: the 18 generic structures framework,” *Journal of Cleaner Production*, vol. 19, no. 6-7, pp. 588–597, 2011.

[44] O. Listeş and R. Dekker, “A stochastic approach to a case study for product recovery network design,” *European Journal of Operational Research*, vol. 160, no. 1, pp. 268–287, 2005.

[45] H. Yu and W. D. Solvang, “A new two-stage stochastic model for reverse logistics network design under government subsidy and low-carbon emission requirement,” in *Industrial Engineering and Engineering Management (IEEM), 2017 IEEE International Conference on*, pp. 90–94, IEEE, 2017.

[46] M. El-Sayed, N. Afia, and A. El-Kharbotly, “A stochastic model for forward–reverse logistics network design under risk,” *Computers & Industrial Engineering*, vol. 58, no. 3, pp. 423–431, 2010.

[47] R. Accorsi, R. Manzini, C. Pini, and S. Penazzi, “On the design of closed-loop networks for product life cycle management: Economic, environmental and geography considerations,” *Journal of Transport Geography*, vol. 48, pp. 121–134, 2015.

[48] N. Kafa, Y. Hani, and A. El Mhamedi, “An integrated sustainable partner selection approach with closed-loop supply chain network configuration,” *IFAC-PapersOnLine*, vol. 48, no. 3, pp. 1840–1845, 2015.

[49] M. Zhalechian, R. Tavakkoli-Moghaddam, B. Zahiri, and M. Mohammadi, “Sustainable design of a closed-loop location-routing-inventory supply chain network under mixed uncertainty,” *Transportation Research Part E: Logistics and Transportation Review*, vol. 89, pp. 182–214, 2016.

[50] S. H. Amin and G. Zhang, “An integrated model for closed-loop supply chain configuration and supplier selection: Multi-objective approach,” *Expert Systems with Applications*, vol. 39, no. 8, pp. 6782–6791, 2012.

[51] F. Dehghanian and S. Mansour, “Designing sustainable recovery network of end-of-life products using genetic algorithm,” *Resources, Conservation and Recycling*, vol. 53, no. 10, pp. 559–570, 2009.

[52] A. Sepúlveda, M. Schluep, F. G. Renaud, M. Streicher, R. Kuehr, C. Hagelüken, and A. C. Gerecke, “A review of the environmental fate and effects of hazardous substances released from electrical and electronic equipments during recycling: Examples from china and india,” *Environmental impact assessment review*, vol. 30, no. 1, pp. 28–41, 2010.

[53] R. Directive, “Directive 2002/95/ec of the european parliament and of the council of 27 january 2003 on the restriction of the use of certain hazardous substances in electrical and electronic equipment,” *Official Journal of the European Union*, vol. 13, p. L37, 2003.

[54] E. Directive, “Directive 2005/32/ec of the european parliament and of the council of 6 july 2005 establishing a framework for the setting of ecodesign requirements for energyusing products and amending the council directive 92/42/eec and directives 96/57/ec and 2000/55,” *EC of the European Parliament and of the Council*, 2005.

[55] R. E. C. R. Turkey, “Atık elektrikli ve elektronik eşyaların kontrolü yönetmeliği belediye uygulama rehberi.,” 2016.

[56] M. Talaei, B. F. Moghaddam, M. S. Pishvaee, A. Bozorgi-Amiri, and S. Gholamnejad, “A robust fuzzy optimization model for carbon-efficient closed-loop supply chain network design problem: a numerical illustration in electronics industry,” *Journal of Cleaner Production*, vol. 113, pp. 662–673, 2016.