A LOGISTICS NETWORK DESIGN FOR TIRE RECOVERY: A CASE STUDY

(LASTİK GERİ KAZANIMI İÇİN LOJİSTİK AĞ MODELİ TASARIMI: VAKA ÇALIŞMASI)

by

Özden Tozanlı, B.S.

Thesis

Submitted in Partial Fulfillment

of the Requirements

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I would also like to express my love and gratitude to my beloved family; for their understanding and endless love, through the duration of my studies. I dedicate this thesis to the most precious people in my life; to my mother and father. I extend my thanks to all my friends for their support and confidence in me.

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Özden TOZANLI
24.05.2013

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ICA	Initial Collection Area
CCC	Centralized Collection Center

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ABSTRACT

A LOGISTICS NETWORK DESIGN FOR TIRE RECOVERY: A CASE STUDY

We consider the problem of designing a logistics network for the collection and reprocessing of used tires. The logistics network consists of used tires collection points, recycling and/or remanufacturing facilities and demand points. Tire remanufacturing, commonly known as tire retreading, and tire recycling are very profitable, yet many companies who reprocess used tires are mostly either doing only recycling or only retreading. Retreading-only companies usually use a make-to-order system where the customers bring them their own tires to be retreaded, i.e. there is one-to-one correspondence between returns and customer orders, whereas recycling companies use a make-to-stock system where the used tires are collected back and after recycling, the resulting products are sold to manufacturers to be used as raw materials or energy sources. We investigate the profitability of adding a tire retreading facility into the logistics network for a company who originally does recycling only. The problem is formulated and solved using mixed integer programming for both single-period and multi-period cases in order to find the optimal design that maximizes the overall profit of the recycling company. Numerical experimentations are conducted to see the effects of changing return parameters on the optimal design and profit.

Keywords : Tire retreading, recycling, reverse logistics network design, mixed integer programming

RESUMÉ

LA CONCEPTION D’UN RESEAU LOGISTIQUE POUR LA RECUPERATION DES PNEUS: UNE ETUDE DE CAS

Nous considérons le problème de concevoir un réseau logistique pour la collecte et le retraitement des pneus usagés. Le réseau logistique se compose des points de collecte des pneus usagés, les installations de recyclage et de rechapage, et de points de demande. Le recyclage et le rechapage des pneus sont très profitable, mais de nombreuses entreprises qui retraitent les pneus usagés font soit seulement le recyclage soit seulement le rechapage. Les entreprise de rechapage utilisent un système de ‘make-to-order’ où les clients apportent eux-mêmes leurs pneus à rechaper, c.à.d. il y a une correspondance de un à un entre les reprises et les commandes des clients, tandis que les entreprises de recyclage utilisent un system de ‘make-to-stock’ où les pneus usagés sont collectés et après le recyclage, les produits qui en résultent sont vendus aux fabricants pour être utilisés comme matières premières ou sources d'énergie. Nous étudions la rentabilité d’ajouter une installation de rechapage des pneus dans le réseau logistique d’une entreprise qui fait seulement le recyclage actuellement. Le problème est formulé et résolu comme un modèle de programmation à nombre entiers mixte à périodes multiples et à produits multiples pour déterminer la conception optimale qui maximise le profit total. Les expérimentes numériques sont faites pour analyser les effets de changer les paramètres des reprises (par ex. le taux des pneus usagés en bonne forme qui peuvent être rechapés) sur la conception et le profit optimaux.

Mots-clés : Rechapage des pneus, recyclage, conception du réseau logistique inverse, programmation à nombre entiers mixte

ÖZET

LASTİK GERİ KAZANIMI İÇİN LOJİSTİK AĞ MODELİ TASARIMI: VAKA ÇALIŞMASI

Bu çalışmada, kullanılmış lastiklerin toplanması ve yeniden kullanımı için lojistik ağ modeli tasarım problemi değerlendirilmiştir. Lojistik ağ modeli, kullanılmış lastikler için toplama merkezleri, geri dönüşüm ve/veya kaplama tesisleri ve talep noktalarından oluşmaktadır. Lastik yeniden üretimi, genel olarak lastik kaplama olarak bilinmektedir. Türkiye'de, yalnızca kaplama yapan ya da geri dönüşüm yapan firmalar faaliyet göstermekte ve bu iki işlemi bir arada yapan bir firma bulunmamaktadır. Yalnızca lastik kaplama yapan tesisler, sipariş üzerine çalışmaktadır. Bu sistemde, müşteri kaplanabilir nitelikte olan lastiği kaplama tesisine getirir ve lastik kaplandıktan sonra lastiği almaya gelir. Geri dönüşüm tesisleri ise stok tutarak üretim yapmaktadır. Bu sistemde ise toplanan kullanılmış lastikler geri dönüşüm tesisine ulaşıtırılır ve tesise ulaşan lastiklerin geri dönüşümü yapılır. Geri dönüşüm sonucu oluşan ürünler, hammadde olarak kullanılmak üzere farklı üreticilere satılır. Kullanılmış lastikler çimento fabrikalarına gönderilerek enerji kazanımı için de kullanılmaktadır. Bu çalışmada, bir geri dönüşüm tesisine lastik kaplama tesisin eklenmesi durumunda oluşacak yeni lojistik ağ modeli ve bu modelin karlılığı incelenmiştir. En iyi ağ tasarımını ve karı bulmak için hem tek dönemli hem de çok dönemli karmaşık tamsayılı modelleri kurulmuş ve karşılaştırılmıştır. Sistem parametrelerindeki değişikliklerin en iyi ağ tasarımı ve karlılık üzerine etkilerini incelemek için sayısal deneyler yapılmıştır.

Anahtar Sözcükler : Lastik kaplama, Geri dönüşüm, Tersine lojistik ağ modeli, karmaşık tamsayılı programlama

1. INTRODUCTION

Solid wastes, which have increased significantly in the last couple of decades due to the increase in consumption rate, cause serious environmental problems. They cause irrecoverable damages to the nature such as the depletion threat of energy resources. Tires are categorized as highly structured rubber products. 65-70% of a tire consists of rubber. Rubber products generates a type of solid waste which take a long time to decompose in nature and causes permanent damages because of their structured components. The disposal of tires is a big issue for both environmental and economical aspects due to the increasing number of vehicles every year. ETRMA (European Tire and Rubber Manufacturers' Association) declares that 3.27 million tons of used tires are generated in 2011, which is around 255 million units of tire. This remarkable volume of used tires added every year not only gets governments' attention to the environmental pollution problems, but also increases the value of product recovery which has a positive impact on the economy and the environment in the long run.

Despite of their heterogeneous composition, used tires are excellent candidates for product recovery. They have higher ecological and economical impact relative to most of the recoverable products such as paper, plastics, batteries etc. According to Gungor and Gupta (1998), product recovery is carried out mainly for three reasons: the hidden economic value of solid waste, market requirements and governmental regulations. The objective of product recovery is not only to reduce the environmental impact by recycling or remanufacturing used tires instead of sending to landfills, but also to gain economical value by supplying cheap resources. While the recovery rate of paper and plastics are 69% and 58%, respectively, the recovery rate of used tires is 95% in Europe, 91% in Japan and 89% in USA. Thus, used tires are the most recovered product globally.

Product recovery options include mainly remanufacturing, recycling, reuse and repair. Thierry et al. (1995) categorize recovery processes as repair, refurbishing, remanufacturing, cannibalization and recycling whereas Gungor and Gupta (1998) simply categorize it as material recovery and product recovery. For the recovery of used tires, Ferrao et al. (2007) divide the recovery options into energy recovery, recycling and retreading. Sienkiewicz et al. (2012) categorizes as retreading, energy recovery, pyrolysis, product recycling and material recycling. Sienkiewicz et al. (2012) remark that the recovery process to use is determined based on the collection and management policies of used tires of the countries. In Turkey, a used tire can be used for energy recovery, recycling and retreading.

Used tires have a wide range of application areas. Fiksel et al. (2010) point out different application types of used tires that include tire-derived fuel, civil engineering, and use of ground rubber for production of artificial turf, asphalt, molded products, and compare the environmental benefits of each application by considering the cost effective opportunity of tire recovering. Ferrer (1996) defines four applications for tire recovery such as heat generation in thermoelectric plants or in cement kilns, ground rubber applications, direct reuse in civil engineering works or recycling through pyrolysis. The existence of such applications motivates tire recovery, which in return decreases the landfilling rate. ETRMA states that the landfilling rate has decreased to 4% from 62% since 1996, which means that a substantial 96% of used tires is now sent to recovery processes.

Apart from energy recovery, used tires are recycled or retreaded consisting of the corrosion of tires. Retreading process is reasonable when lower corrosion is occurred, i.e. the outer layer of tire is corroded while inner structure is in a good condition. Retreading can be simply defined as the process consisting of the replacement of the worn-out tread by a new one. Beukering and Jannsen (2001) define retreading as to recloth the old casting with a tread made from new materials, and they indicate that 80% of raw material and energy necessary for production of a new tire is saved and disposal quantity of used tires is reduced with retreading. Retreading process extends lifetime of tires. A tire can be retreaded several times as long as inner structure of tire is undamaged. Retreading is mainly applied to truck, bus and aircraft tires, only some passenger car tires can be retreaded. Retread tires have same road performance and take same mileage compared to new tires while their selling price is 30-50% lower than a new tire price. Regarding to ETRMA, 297,000 tons of tires out of 3.266 million tons of used tires were retreaded in 2011, whereas it is 258,000 tons of tires out of 3.273 million of tires in 2010.

Tire recycling is the recovery option that is used in order to supply cheap resource for producing new products such as cable, mat, conveyor belt, artificial turfs, road embankment, heat insulation, playgrounds, etc., and it is also used in civil engineering applications like asphalt production. Two recycling processes exist for used tires: mechanical and chemical. 65%-70% of a truck tire consists of rubber and the remaining components are steel wire, textile fibers and outages. In mechanical process, tires are shredded into small pieces in order to separate their components. After shredding, steel and fabric components are separated from tire, and remaining rubber is reduced to granule. 65% of granule, 25% of steel wire and 10% of textile fibers and outages result by shredding of a truck tire. As alternative to mechanical process, a chemical process known as pyrolysis is applied in order to decompose substances of tires. Pyrolysis produces 35-45% of carbon black, 35-42% oil, 12-15% of steel wire and 7-12% of gas. Carbon black is used for producing rubber products. It is known to increase durability, strength and performance of rubber. Oil and gases are used as energy resources, in either cement facilities or recycling facilities. Although the existence of a wide range of applications for the products resulting from pyrolysis increases the economic value of this recovery process, pyrolysis requires high temperature to process and its implementation is harder and more expensive than the mechanical shredding process. For this reason, only a few recycling facilities use pyrolysis worldwide. Most pyrolysis facilities are located in Korea, Russia and Ukraine.

The weight of a new truck tire may change from country to country. For instance, the tire weight is approximately equal to 54 kg and 65 kg in USA and Europe, respectively. Moreover, the difference between weights of new and used tires is around 9 kg. Due to variance of tire weights by countries, materials that are produced by both mechanical and chemical recycling processes vary. Sienkiewicz (2012) investigates the proportions of resources that are produced by mechanical recycling process in USA and Europe. The proportions of resources that are produced by mechanical recycling in Turkey is shown in Table 1.1 with comparison to USA and Europe.

Table 1.1. The proportions of products resulting from mechanical recycling process

Materials		in Turkey	in Europe	in USA
Granule (%)		65	65	69
Steel (%)		25	25	15
Textile Fibers & Outages (%)		10	10	16
Average weight	New Tire	60	65	54
	Scrap Tire	51	56	45

One of the most common application fields of used tires is energy recovery. Tires are used as energy sources in many industries such as cement, paper, lime etc., because they generate higher energy when combusted compared to coal. The combustion of used tires is widely used in cement industry. Sienkiewicz et al. (2012) state that the combustion of tires in cement kilns is environmentally safer than coal combustion because they emit much lower level of dusts, carbon dioxide, nitrogen oxides and heavy metals.

Currently, in Turkey, there are three chemical and nine mechanical recycling companies, and thirty cement facilities that have legal permit for combusting tires as energy resource (Lastik Sanayicileri Dernegi). While 80% of used tires collected in a year are sent to recycling facilities, 20% of used tires collected in a year are sent to cement facilities. Retreading process is not considered as part of the logistics network of tire recovery in Turkey, thus, this process is not considered in the existing network. The percentage of processes can be changed by countries, i.e. large proportion of used tires are combusted for energy recovery in Japan, and it is more than double that in Korea.

75% of used tires are recycled in Korea, while retreading is the most popular tire recovery option in the USA (Jang et al., 1997).

The economic and environmental benefits of collecting and recovering used tires pushed governments to make the tire manufacturers and stakeholders responsible for collecting and controlling the recovery process of used tires through legislations or regulations. These regulations vary by countries. For instance, Jang et al. (1997) state that tire manufacturers are responsible for collecting, transporting, processing and storing in market in USA, while in Korea and Japan responsibilities are determined for collection to landfill. In Europe, three different systems are used for managing recovery of used tires: producer responsibility system, tax system and free market system. EU countries have to use one of these three systems. Tax system, which is a system where producers and stakeholders are required to add a tax for tire production and to the price of new tires that are sold to customers, is applied in Denmark and Slovak Republic. Free market system is a system where all operators are responsible for tire recovery by legislation, thereby voluntary cooperation is prompted. This system is used in Austria, Croatia, Germany, Ireland, Switzerland (ETRMA, 2011). Most of EU countries use producer responsibility system, which is considered as the most appropriate system for keeping recovery chain under control and obtaining the highest recovery rate. According to this system, producers are obligated by legislations to control each stage of recovery process from collecting used tires to recovery.

From logistics point of view, product recovery process begins with collection of used tires. Tire manufacturers are obligated to collect a certain proportion of used tires whose value is determined by governments considering the previous sales of new tires. While the proportion of tires to be collected was 30% in 2007, this proportion is increased each year and reached to 60% in 2012. Potential collection points such as tire repair & maintenance shops, vehicle dealers etc., where consumers give scrap tires feeless, are visited in order to collect used tires. Collected tires are sent to retreading, recycling or cement facilities depending on their conditions as well as the facility capacities. In Turkey, retreading companies use make-to-order system, i.e. customers bring their own tires to the facility for retreading, and they take back the retread tires, in other words these companies do not collect used tires for their business. On the other hand, the tire recycling companies collect used tires and after recycling them, the resulting materials are sold to customers. In this study, a tire recycling company which uses mechanical recycling is considered as a case study, The company considers adding tire retreading into their tire recovery business. We investigate here the profitability of adding a tire retreading facility into the logistics network of the recycling company. The optimal logistics network and the optimal profit for the new combined retreading & recycling business is determined using mathematical programming.

This thesis is organized as follows: A literature survey is provided in Chapter 2. In Chapter 3, the solution methodology for the tire recovery problem is described, and mathematical programming models are formulated for both single-period and multi-period cases. In Chapter 4, numerical experimentations are provided. Finally, Chapter 5 concludes the thesis and suggests future work.

2. LITERATURE SURVEY

Product recovery is studied from different point of views in the literature. While some studies aim to find an alternative recovery model to an existing one, some studies aim to increase the profitability of an existing recovery model. For instance, Mutha and Pokharel (2008) emphasize the importance of reverse logistics in order to decrease disposal rate that incurs with large costs as well as reducing the cost of new products. Sasikumar et al. (2010) mainly address the remanufacturing part of product recovery. According to them, remanufacturing is a very important field of product recovery since through remanufacturing, the used products is restored to a like-new condition having the same characteristics as a new product in terms of technical performance.

Even though there are numerous different studies regarding tire recovery, all studies have a common objective which is to obtain a positive economic and environmental contribution through tire recovery. Beukering and Jansen (2001) have tested the economical, environmental and social effectiveness of trade measures of life cycle of truck tire in Eastern and Western Europe by dividing the life cycle of tire into three stages which are production, consumption and solid waste management. They investigate which stage of the life cycle has the highest environmental and economical gain. They develop a two-region simulation model which integrates the complete life cycle, incorporates environmental impacts in its economic analysis, and allows for variations in trade of new and old truck tires. Similarly, Fiksel et al. (2011) use a life cycle assessment methodology to compare the environmental benefits of different used tire applications which reduce landfilling rate of used tires.

Logistics network design problems for product recovery are mainly considered as closed loop supply chain (CLSC) design problems, which are mostly formulated as multi-period mixed integer programming models. CLSC studies aim to find the best set of inventory, transportation, and production decisions by taking into consideration the environmental concerns, which are mostly related to product recovery operations. Beamon and Fernandes (2004) design a closed-loop supply chain to determine where to open warehouses and collection centers, and the quantities of transported products. They formulate the problem as a multi-period mixed integer programming model where they use the present worth method in order to analyze the present equivalent of future costs. Similarly, Ozkır and Basligil (2012) study a general CLSC design problem that includes consumers, collection points, reverse centers, plants, distribution centers, and recovery facilities by formulating a multi-product, multi-echelon, and multi-period model in order to determine the optimal number of each facility type and their locations which maximize the profit of the CLSC network. Unlike the other studies, they add an additional constraint for not closing a facility which has already been opened in the previous periods in order to prevent extra setup costs that occur by opening or closing facilities.

Benaissa and Benabdelhafid (2010) conduct a study for facility location problem for a reverse logistics network. Their model is formulated and solved as multi-period mixed integer linear programming for determining the state of sites, their opening, closure, available capacity and material flow between the various entities of the logistics network by minimizing the overall costs. Their work has two features: the first one is to address the classical network of end-of-life product treatment problem with a generic model and the second is to establish a multi-product and multi-period location of sites for the reverse logistics of the end of life products. Similar to Benaissa and Benabdelhafid (2010), Salema et al. (2006) consider the problem of designing a reverse logistics network for which they build a warehouse location-allocation model that simultaneously optimizes the forward and reverse networks. First, they propose a single product mixed integer linear model with unlimited capacity, and then, they extend it to a multi-product mixed integer linear capacitated recovery network model. Two numerical examples are used to compare models.

Aras and Aksen (2007) address the problem of locating collection centers for a company who aims to collect used products from consumers. A drop-off strategy is assumed, according to which product holders bring the used products to the collection centers that are established by the company. In collection centers, returned items are categorized based on their quality level, and a different incentive is offered for each return type. The problem is formulated as a mixed-integer nonlinear facility location-allocation model which determines both the optimal locations of the collection centers and the optimal incentive values for each return type that maximize the profit from returns. They use two heuristic methods which are Tabu search and Fibonacci search heuristics. The Tabu search heuristic finds a feasible solution in the space of candidate sites of collection center locations, and the Fibonacci search aims to find the best incentive for each return type for a given location set.

Only a few studies can be found in the literature regarding tire recovery network design. To the best of our knowledge, there is no study that considers both recycling and retreading processes in one logistic network. Sasikumar et al. (2010) study the problem of designing a logistics network for truck tire recovery by considering only tire retreading as tire recovery option whereas Dehghanian and Mansour (2009) considers only tire recycling as tire recovery option. Sasikumar et al. (2010) presents a real-life case study for truck tire remanufacturing. They develop a mixed integer nonlinear programming model in order to maximize the profit of a multi-echelon reverse logistics network. The proposed model is solved to find the number of facilities to open, their locations and the allocation of product flows. The results of this study reveal that the retread tires are profitable for both customers and retreading companies. Dehghanian and Mansour (2009) design a sustainable recovery network model by balancing economical, environmental and social impact of recovery. They develop three-objective mathematical model where two of the objectives are to maximize economical and social impacts and one is to minimize negative environmental impact. Environmental impact is investigated by using life cycle analysis (LCA) which provides to find the impact of different end-of-life (EOL) options. Social impacts are calculated by using analytical hierarchy process (AHP), and multi-objective genetic algorithm is implemented in order to find the Pareto-optimal solutions, each representing a different network design due to location and technology type of the recycling plants.

To the best of our knowledge, no study is conducted which considers both recycling and retreading process in a logistics network. This study investigates the profitability of adding a tire retreading facility into the logistics network for a company who originally does recycling only. We first develop a multi-product single period mixed integer model for this problem and then extend it to the multi-product case in order to find the optimal logistics network design for tire recovery which maximizes the overall profit of the recycling company.

3. A LOGISTICS NETWORK DESIGN MODEL FOR TIRE RECOVERY

3.1. Problem Definition

Turkish government uses a Producer Responsibility System in order to control tire recovery process. According to this system, the responsibility of controlling the entire tire recovery network is given to tire manufacturers by some legislations. This system seems the most appropriate model for not only keeping the recovery chain under control and obtaining the highest recovery rate, but also managing the recovery process in the most economical way. In order to carry out this regulation system, tire manufacturers are cooperated and founded a non-profit organization, named LASDER, which authorizes some companies such as recycling companies, individual stockers or collectors to collect and recover the used tires on behalf of tire manufacturers in Turkey.

Tire recovery can be done by three ways: tire retreading, recycling or combustion in cement facilities for energy recovery. However, the existing logistics network for tire recovery in Turkey consists usually of recycling and energy recovery processes. Companies who recover used tires are either doing only recycling or only retreading in Turkey, while in some countries, recycling facilities retread tires as well. Retreading-only companies operate independently from the logistics networks for tire collection and recovery, they usually use a make-to-order system where customers bring their own retreadable tires to the facilities, and after retreading process, they take the retread tires back from facility.

Tires are allowed to be stocked at most 60 days because of the fire or infestation risk. Thus, generally, recycling companies prefer to recycle all used tires that come to the facility instead of stocking used tires. Demanded volume of recycled products are sold and the remaining is held in stock. Therefore, recycling companies use a make-to-stock system where the used tires are collected back and recycled. The resulting products from recycling are sold to manufacturers to be used as raw materials or energy sources.

In the existing logistics network of tire recovery, tires collected back from customers are directly sent to either recycling facility or cement facility without controlling whether the incoming tires are retreadable. If the capacity of the recycling facility is exceeded, the excess amount of used tires is sent to cement facility for energy recovery. All tires received by recycling facility are recycled even if they are retreadable, i.e. in good condition. Customers come to buy the products resulting from recycling, thus, there is no transportation cost that occurs for the recycling facility. The unit transportation cost of sending used tires to cement facility is higher than sending to the recycling facility, because recycling process is highly preferred so that it provides cheap resources to produce different various products.

In this study, a tire recycling company which is authorized for controlling logistics network of tire recovery process from collection to recycling process is considered as a case study. The profitability of adding a tire retreading facility into the logistics network of this recycling company is investigated.

3.2. The Proposed Logistics Network Model

In this section, the proposed logistics network design model is formulated. Since the retreading option does not exist in the existing logistics network of the recycling company, it is added to the existing logistics network design of the recycling company. The integrated logistics network model for the collection and recovery of used tires is shown in Figure 3.1. According to this network, consumers bring used tires to the small shops which are located in the initial collection areas (ICAs), i.e. tire repair & maintenance shops, vehicle dealer, auto services etc., at the very first stage. Since customers bring used tires directly to ICAs, there is no transportation cost that occurs for the company in this stage between customers and ICAs. The quantity of used tires supplied by each ICA is equal to the total amount of used tires returned by customers in that area. Used tires supplied by ICAs are collected by the company and sent to centralized collection centers (CCCs). CCCs are intermediate centers that not only do inspection of returns, but also do sorting and cleaning. In actual situation, the considered company has no CCCs, thus, tires are directly brought to recycling facility from ICAs. In this case, used tires are recycled even if they are in good condition for retreading. In order to inspect the used tire condition, the company considers opening capacitated CCCs in some locations.

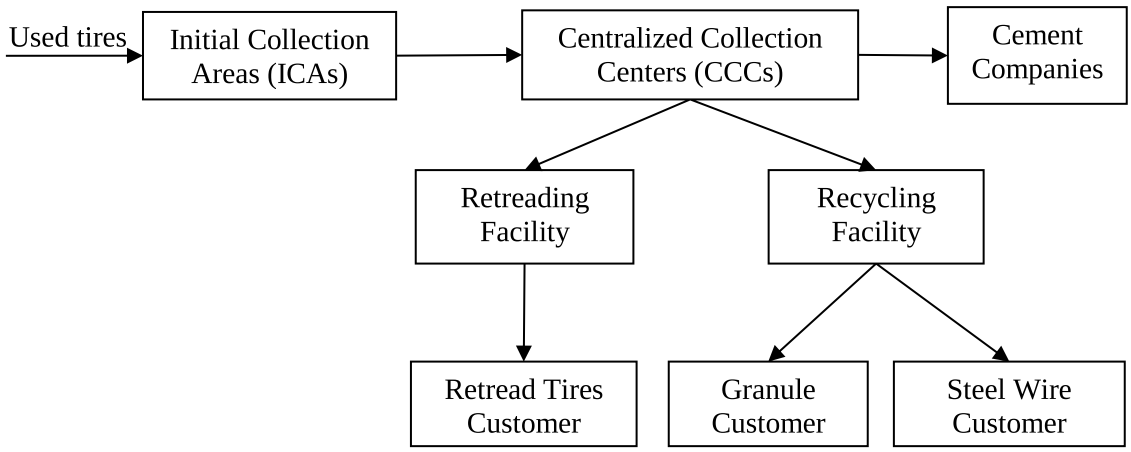

Figure 3.1. The logistics network for tire recycling and retreading

After inspection of returns in CCCs, used tires are categorized as retreadable or not retreadable (thus, recyclable). It is estimated that a certain proportion of used tires received by CCCs are retreadable. All retreadable tires are sent to retreading facility. Since a retread tire has similar road performance as a new tire and also it has a price advantage, most logistics and coach companies prefer to use retread tires, thus a significant demand occurs for retread tires. Customers come to buy retread tires from the retreading facility, thus no outbound transportation cost occurs for the company.

The non-retreadable tires are primarily sent to recycling facility considering the capacity constraint of the recycling facility. Since the company uses mechanical recycling method, there are two types of products which are granule and steel wire that result from recycling. Similar to retread tires, customers come to buy products from the recycling facility, thus again, no transportation cost occurs for the company. Any excess volume of used tires, which cannot be sent to recycling facility because of the capacity, is sent to cement facilities for energy recovery.

3.3. Methodology

In order to determine the profitability of adding a tire retreading facility to the recycling company's logistics network, two models are formulated: one model corresponds to the actual case, i.e. the recycling-only case, which will be referred to as Model I and the other model corresponds to the case where retreading facilities and CCCs are added to the logistics network, which will be referred to as Model II. The profitability of the new network is determined by comparing the profits of Models I and II. Furthermore, this problem is studied for two cases regarding the planning horizon: single-period and multi-period cases. First, the problem is considered as single period, and it is formulated and solved as a multi-product single period mixed integer programming. Then, the model is extended to consider multiple periods. Both models aim to find the optimal logistics network design for tire recovery which maximizes the overall profit of the recycling company.

3.3.1. Assumptions

The aim of the proposed model is to determine where to locate CCCs and retreading facilities in order to maximize the profit. The profit is calculated considering sales revenues and costs of setup, production, operating and transportation. The problem is deterministic, i.e. the parameters of the model such as supply amounts of used tires, demands for different products, cost parameters, retreadable tire ratio, etc. are assumed to be known with certainty. The problem is modeled as single period and multi-period multi-product mixed integer programming (MIP), and in the objective function of multi-period model, the present equivalent of the future costs is considered.

The following assumptions are used in the model:

- Turkey is divided into eight regions and aforementioned recycling company is authorized to collect used tires from Marmara Region. There are 16 ICAs, each representing a city located in Marmara Region.

- Each period represents each year.

- Government regulations require the collection of a certain volume of used tires which is calculated as a certain proportion of previous year's tire sales. This quota is increased in each year, and from 2007 through 2013, this quota has increased from 30% to 70%, respectively. For instance, while tire manufacturers are obligated to collect back in 2007 at least 30% of tires that are sold in 2006, they are obligated to collect back in 2013 at least 70% of tires that are sold in 2012.

- Quantities of used tires supplied by each ICA are determined based on population size of the city where ICA is located. Used tires sent from each ICA might be allocated to different CCCs.

- Quantities of used tires supplied by ICAs, volume of used tires sent to CCCs from ICAs; volume of used tires sent to recycling facility from CCCs; or volume of used tires sent to cement facilities from CCCs are in unit of tons, while volume of used tires sent to retreading facility from CCCs is in unit of tires.

- All fixed and variable costs are known for each period. Additionally, all variable costs are same for all retreading facilities and recycling facility.

- Unit production cost of recycling is included in operating cost of recycling facility.

- Unit transportation cost of sending used tires to CCCs from ICAs, to recycling facilities from CCCs, to retreading facilities from CCCs are the same. Since the government encourages a higher recycling rate, the transportation cost of used tires sent to cement facilities is considered to be more expensive. All transportation costs are per unit distance and unit tons or tires sent.

- Possible locations of CCCs and retreading facilities are known and same for each period. Once a facility is open in some location, it stays open for all periods in the planning horizon.

- CCCs, retreading facilities and recycling facility are capacitated and capacities are same in each period.

- A certain proportion of volume of returns received by each CCC is retreadable. This proportion will be referred to as retreadable tire ratio hereafter. Since there is a huge demand for retread tires, all retreadable tires received by retreading facility are retread and sold.

- Since, used tires cannot be stocked more than 60 days due to some legislations, all used tires received by the recycling facility are recycled in each period, and any excess volume of products resulting from recycling are stocked and carried to the next period.

- Excess volume of products resulting from recycling are sold at a very low price (i.e. a very low salvage value) in single-period model.

- Since cement facilities need huge volume of used tires to combust for energy, the volume of used tires that are not recycled are sold to cement facilities.

3.3.2. Single-Period Multi-Product Mixed Integer Programming Model

Single-period model is considered in order to analyze the profitability of the company if the demand and supply patterns are not expected to change significantly from one period to another and the end-of-period inventories are not welcome by the tire recovery company. Model I considers the actual case for the recycling-only company. The proposed case where the tire retreading option is added to tire recovery business is considered by Model II, as shown below.

Model I-Single period

Sets, parameters and variables of Model I are explained below:

Sets

i : Index for ICA, $i \in I$

m : Index for cement company, $m \in M$

n : Index for products resulting from recycling, $n \in N$

Parameters

p_n^{RC} : The selling price per ton of the product *n* resulting from recycling

p^{CF} : The selling price per ton of scrap tires to cement facility

SV : Salvage value for recycled products

K^{RC} : Capacity of recycling facility

OC^{RC} : Operating cost of recycling facility

Q_i : Quantity of used tires supply by ICA *i*

TR : Transportation cost/ton, unit distance from ICAs to recycling facility

TR^{CF} : Transportation cost/ton, unit distance from CCCs to cement facilities

d_i^{RC} : Distance from ICA *i* to recycling facility

d_{im}^{CF} : Distance from ICA *i* to cement facility *m*

e_n : The rate of product *n* (in percentage) produced at recycling facility

D_n^{RC} : Demand for product *n* produced at recycling facility

Variables

V_i^{RC} : Volume of tires sent from ICA *i* to recycling facility

V_{im}^{CF} : Volume of tires sent from ICA *i* to cement facility *m*

V_n^{RCP} : Volume of product *n* produced in recycling facility

U_n^- : Unsatisfied demand for product *n* at the end of period

U_n^+ : Excess volume of product *n* at the end of period

Objective Function

The objective is to find the profitability of current logistics network for the recycling company in single-period case. The objective function consists of total revenues and costs regarding logistics network. Expression (3.1) represents sales revenues from the materials resulting from recycling and used tires sold to cement facilities. Expression (3.2) represents salvage value that comes from the sales of the excess recycled products at the end of the period. Expression (3.3) represents total transportation costs of sending used tires between facilities of the network. Operating cost of recycling facility is considered as fixed cost and it is added later to the optimal objective function value that is found by solving the model in order to calculate the total profit of tire recycling business.

A simple definition of objective function can be shown as:

max z= (Sales Revenues + Salvage Value) - Transportation Costs

The mathematical formulation of the objective function is given below :

Sales Revenues:

$$\sum_n p_n^{RC}(D_n^{RC} - U_n^-) + \sum_m \sum_i p^{CF} V_{im}^{CF} \tag{3.1}$$

Salvage Value:

$$\sum_n U_n^+ SV \tag{3.2}$$

Transportation Costs:

$$\sum_i TRV_i^{RC} d_i^{RC} + \sum_m \sum_i TR^{CF} V_{im}^{CF} d_{im}^{CF} \tag{3.3}$$

Constraints

Expression (3.4) defines that the volume of used tires received by ICA *i* has to be sent to one of two facilities which are either recycling or cement facilities. Therefore, this constraint makes sure that the outgoing flow from each ICA is less than or equal to the supply amount by each ICA.

$$V_i^{RC} + \sum_m V_{im}^{CF} \leq Q_i \;\; , \;\; \forall i \in I \tag{3.4}$$

Expression (3.5) represents the capacity constraint of recycling facility. In this equation, total volume of used tires sent from each ICA to the recycling facility cannot exceed the capacity of recycling facility.

$$\sum_i V_i^{RC} \leq K^{RC} \tag{3.5}$$

Expression (3.6) determines the volume of product n produced by recycling facility.

$$V_n^{RCP} = e_n \sum_i V_i^{RC}, \quad \forall n \in N \tag{3.6}$$

Expression (3.7) calculates the excess or the unsatisfied demand for product n at the end of the period.

$$U_n^+ - U_n^- = V_n^{RCP} - D_n^{RC}, \quad \forall n \in N \tag{3.7}$$

Model II-Single period

Sets, parameters and variables of model II are explained below:

Sets

i : Index for ICA, $i \in I$

j : Index for CCC, $j \in J$

l : Index for retreading facility, $l \in L$

m : Index for cement company, $m \in M$

n : Index for products resulting from recycling, $n \in N$

Parameters

r : Retreadable tire ratio

W : The multiplier to convert one ton of tires to unit tires

c^{RT} : Unit retreading cost of tires

p^{RT} : Unit selling price of retreaded tire

p_n^{RC} : The selling price per ton of the product *n* resulting from recycling

p^{CF} : The selling price per ton of scrap tires to cement facility

SV : Salvage value for recycled products

K_j^{CCC} : Capacity of CCC *j*

K_l^{RT} : Capacity of retreading facility *l*

K^{RC} : Capacity of recycling facility

S_j^{CCC} : Setup cost of opening CCC *j*

S_l^{RT} : Setup cost of opening retreading facility *l*

OC_l^{RT} : Operating cost of retreading facility *l*

OC_j^{CCC} : Operating cost of CCC *j*

OC^{RC} : Operating cost of recycling facility

Q_i : Quantity of used tires supply by ICA *i*

TR : Transportation cost/ton, unit distance from ICAs to CCCs, from CCCs to recycling facility or retreading facilities

TR^{CF} : Transportation cost/ton, unit distance from CCCs to cement facilities

d_{ij}^{CCC} : Distance from ICA *i* to CCC *j*

d_{jl}^{RT} : Distance from CCC *j* to retreading facility *l*

d_j^{RC} : Distance from CCC *j* to recycling facility

d_{jm}^{CF} : Distance from CCC *j* to cement facility *m*

e_n : The rate of product *n* (in percentage) produced at recycling facility

D_n^{RC} : Demand for product *n* produced in recycling facility

Variables

V_{ij}^{CCC} : Volume of tires sent from ICA *i* to CCC *j*

V_{jl}^{RT} : Volume of retreadable tires sent from CCC *j* to retreading facility *l*

V_j^{RC} : Volume of tires sent from CCC *j* to recycling facility

V_{jm}^{CF} : Volume of tires sent from CCC *j* to cement facility *m*

V_n^{RCP} : Volume of product *n* produced in recycling facility

U_n^- : Unsatisfied demand for product *n* at the end of period

U_n^+ : Excess volume of product *n* at the end of period

$$X_j = \begin{cases} 1 & \text{if CCC } j \text{ is opened} \\ 0 & \text{otherwise} \end{cases}$$

$$Y_l = \begin{cases} 1 & if \text{ retreading facility } l \text{ is opened} \\ 0 & \text{otherwise} \end{cases}$$

$$Z = \begin{cases} 1 & if \text{ recycling facility is operated} \\ 0 & \text{otherwise} \end{cases}$$

Objective Function

The objective is to find the optimal logistics network design that maximizes the total profit in single-period case by determining which facilities to open. The objective function consists of total revenues and costs. Expression (3.8) represents sales revenues coming from the sales of retread tires, recycled products, or used tires to cement facilities. Expression (3.9) represents salvage value that comes from the sales of the unsold recycled products at the end of the period. Expression (3.10) represents setup costs of establishing CCCs and retreading facilities. Expression (3.11) represents cost of retreading used tires. Since the unit production cost of recycling used tires is given in operating costs by the recycling company, total production costs of recycling used tires are included in the operating costs of the recycling facility. Expression (3.12) represents total operating costs of CCCs, retreading facilities and recycling facility. Expression (3.13) represents total transportation costs for sending units from one facility to another in the network.

A simple definition of objective function can be shown as:

max z= (Sales Revenues + Salvage Value) - (Setup Costs + Retreading Costs + Operating Costs + Transportation Costs)

The mathematical formulation of the objective function is given below :

Sales Revenues:

$$\sum_l \sum_j p^{RT} w V_{jl}^{RT} + \sum_n p_n^{RC} (D_n^{RC} - U_n^-) + \sum_m \sum_j p^{CF} V_{jm}^{CF} \tag{3.8}$$

Salvage Value:

$$\sum_n U_n^+ SV \tag{3.9}$$

Setup Costs:

$$\sum_j S_j^{CCC} X_j + \sum_l S_l^{RT} Y_l \tag{3.10}$$

Retreading Costs:

$$\sum_l \sum_j c^{RT} w V_{jl}^{RT} \tag{3.11}$$

Operating Costs:

$$\sum_j OC_j^{CCC} X_j + \sum_j OC_l^{RT} Y_l + OC^{RC} Z \tag{3.12}$$

Transportation Costs:

$$\sum_j \sum_i TRV_{ij}^{CCC} d_{ij}^{CCC} + \sum_l \sum_j TRV_{jl}^{RT} d_{jl}^{RT} + \sum_j TRV_j^{RC} d_j^{RC} + \sum_m \sum_j TR^{CF} V_{jmt}^{CF} d_{jm}^{CF} \tag{3.13}$$

Constraints

Expression (3.14) represents that total volume of used tires sent from ICA *i* to CCC *j* is less than or equal to the used tire supply capacity of ICA *i*.

$$\sum_j V_{ij}^{CCC} \leq Q_i \ , \ \ \forall i \in I \tag{3.14}$$

Expression (3.15) represents that the total volume of used tires sent from ICAs to CCC *j* cannot exceed the capacity of CCC *j*.

$$\sum_i V_{ij}^{CCC} \leq K_j^{CCC} X_j \ , \ \ \forall j \in J \tag{3.15}$$

Expression (3.16) defines that the volume of used tires received by CCC *j* has to be sent to one of three facilities which are retreading, recycling, or cement facilities. This constraint makes sure that the incoming flow to each CCC is equal to outgoing flow from each CCC.

$$\sum_i V_{ij}^{CCC} = V_j^{RC} + \sum_l V_{jl}^{RT} + \sum_m V_{jm}^{CF} \ , \ \ \forall j \in J \tag{3.16}$$

At least one retreading facility is opened as shown by Expression (3.17).

$$\sum_l Y_l \geq 1 \tag{3.17}$$

A certain proportion of used tires that are collected from customers, represented by *r*, is retreadable. Expression (3.18) determines the retreadable tire volume received by CCC *j* considering the retreadable tire ratio *r*.

$$\sum_l V_{jl}^{RT} \leq \sum_i V_{ij}^{CCC} r \quad , \quad \forall j \in J \tag{3.18}$$

Total volume of used tires sent from CCCs to retreading facility *l* cannot exceed the capacity of retreading facility *l* as shown by Expression (3.19).

$$\sum_j w V_{jl}^{RT} \leq K_l^{RT} Y_l \quad , \quad \forall l \in L \tag{3.19}$$

Expression (3.20) represents the capacity constraint of recycling facility. In this equation, total volume of used tires sent from CCCs to the recycling facility cannot exceed the capacity of recycling facility.

$$\sum_j V_j^{RC} \leq K^{RC} Z \tag{3.20}$$

Expression (3.21) determines the volume of product *n* produced by recycling facility.

$$V_n^{RCP} = e_n \sum_j V_j^{RC}, \ \ \forall n \ \in N \tag{3.21}$$

Expression (3.22) calculates the excess or the unsatisfied demand for product n at the end of the period.

$$U_n^+ - U_n^- = V_n^{RCP} - D_n^{RC}, \ \ \forall n \ \in N \text{ and } \forall t \in T \tag{3.22}$$

3.3.3. Multi-Period Multi-Product Mixed Integer Programming Model

In this section, single-period model is extended to multi-period model to model a situation where different demand/supply amounts for products are estimated for the future periods and the inventory carrying is allowed from one period to another for the products resulting from recycling. Each period in the extended model represents each year. Again, the recycling-only case is considered in Model I, and the proposed integrated recycling/retreading case is considered in Model II. Sets, parameters, variables, and the mathematical formulation of the models are shown below.

Model I-Multi-Period

Sets, parameters, variables, and mathematical of the model are shown below:

Sets

i : Index for ICA, $i \in I$
m : Index for cement company, $m \in M$
n : Index for products resulting from recycling, $n \in N$
t : Time period, $t \in T$

Parameters

p_{nt}^{RC} : The selling price per ton of the product *n* resulting from recycling in period *t*
p_t^{CF} : The selling price per ton of scrap tires that are sold to cement facility in period *t*
K^{RC} : Capacity of recycling facility
OC_t^{RC} : Operating cost of recycling facility in period *t*
Q_{it} : Quantity of used tires supply by ICA *i* in period *t*
TR_t : Transportation cost/ton, unit distance from ICAs to recycling facility
TR_t^{CF} : Transportation cost/ton, unit distance from ICAs to cement facilities in period *t*
d_i^{RC} : Distance from CCC *j* to recycling facility
d_{im}^{CF} : Distance from CCC *j* to cement facility *m*
e_n : The rate of product *n* (in percentage) produced in recycling facility
h_{nt}^{RC} : Holding cost per ton per period for product *n* resulting from recycling in period *t*
D_{nt}^{RC} : Demand for product *n* produced in recycling facility in period *t*

Variables

V_{it}^{RC} : Volume of tires sent from ICA *i* to recycling facility in period *t*
V_{imt}^{CF} : Volume of tires sent from ICA *i* to cement facility *m* in period *t*
V_{nt}^{RCP} : Volume of product *n* produced in recycling facility in period *t*
U_{nt}^{-} : Unsatisfied demand for product *n* at the end of period *t*
U_{nt}^{+} : Excess volume of product *n* at the end of period *t*

Objective Function

The objective is to find optimal logistics network design that maximizes the overall profit for multi-period case by determining which facilities to open. The objective function consists of four equations which represent total revenues and costs over the planning horizon. Compared to the objective function of the single-period model, in the multi-period model, the holding cost is considered additionally. Moreover, variable costs such as operating or transportation costs and sales revenues are considered for every time period. Salvage value of unsold product *n* is not considered in this model, because the unsold product *n* in a period is carried to the next period. A brief definition of the objective function is given below.

Expression (3.23) represents sales revenues from recycling, recycled products, or used tires sold to cement facilities. Since the unit production cost of recycling used tires is given in operating cost by the recycling company, total production costs of recycling used tires are included in operating costs. Expression (3.24) represents total operating costs of the recycling facility. Expression (3.25) represents total transportation cost of sending used tires between operators of network. The additional Expression (3.26) represents the total holding cost for products resulting from recycling.

A brief definition of the objective function can be shown as:

max z= Sales Revenues - (Operating Costs +Transportation Costs + Holding Costs)

The mathematical formulation of the extended objective function is given below :

Sales Revenues:

$$\sum_t \sum_n p_{nt}^{RC} (D_{nt}^{RC} - U_{nt}^{-}) + \sum_t \sum_m \sum_i p_t^{CF} V_{imt}^{CF} \tag{3.23}$$

Operating Costs:

$$\sum_t OC_t^{RC} \tag{3.24}$$

Transportation Costs:

$$\sum_t \sum_i TR_t V_{it}^{RC} d_i^{RC} + \sum_t \sum_m \sum_i TR_t^{CF} V_{imt}^{CF} d_{im}^{CF} \tag{3.25}$$

Holding Cost :

$$\sum_t \sum_n h_{nt}^{RC} U_{nt}^{+} \tag{3.26}$$

Constraints

Expression (3.27) represents that the volume of used tires received by ICA i has to be sent to one of two facilities which are recycling or cement facilities in each period. Therefore, this constraint makes sure that the incoming flow to each ICA is less than or equal to outgoing flow from each ICA.

$$V_{it}^{RC} + \sum_m V_{imt}^{CF} \leq Q_i \ , \ \forall i \in I \text{ and } \forall t \in T \tag{3.27}$$

Expression (3.28) represents the capacity constraint of recycling facility in each period. In this equation, total volume of used tires sent from ICAs to the recycling facility cannot exceed the capacity of recycling facility in period t.

$$\sum_i V_{it}^{RC} \leq K^{RC} \ , \ \forall t \in T \tag{3.28}$$

Expression (3.29) determines the volume of product n produced by recycling facility in each period.

$$V_{nt}^{RCP} = e_n \sum_i V_{it}^{RC}, \ \forall n \in N \text{ and } \forall t \in T \tag{3.29}$$

Expression (3.30) represents the inventory balance constraint regarding to product *n*. Customer demand for recycled product n can be met by either the production in recycling facility in period *t* or the stock on hand coming from previous period *t-1*.

$$U_{nt}^{+} - U_{nt}^{-} = U_{n,t-1}^{+} + V_{nt}^{RCP} - D_{nt}^{RC}, \quad \forall n \in N \text{ and } \forall t \in T \tag{3.30}$$

Model II-Multi-Period

Sets, parameters, variables, and mathematical of model II for multiple periods case are shown below:

Sets

i : Index for ICA, $i \in I$

j : Index for CCC, $j \in J$

l : Index for retreading facility, $l \in L$

m : Index for cement company, $m \in M$

n : Index for products resulting from recycling, $n \in N$

t : Time period, $t \in T$

Parameters

r : Retreadable tire ratio

W : The multiplier to convert one ton of tires to unit tires

c_t^{RT} : Unit retreading cost of tires

p_t^{RT} : Unit selling price of retreaded tire in period *t*

p_{nt}^{RC} : The selling price per ton of the product *n* resulting from recycling in period *t*

p_t^{CF} : The selling price per ton of scrap tires to cement facility in period *t*

K_j^{CCC} : Capacity of CCC *j*

K_l^{RT} : Capacity of retreading facility *l*

K^{RC} : Capacity of recycling facility

S_j^{CCC} : Setup cost of opening CCC *j*

S_l^{RT} : Setup cost of opening retreading facility *l*

OC_{lt}^{RT} : Operating cost of retreading facility *l* in period *t*

OC_{jt}^{CCC} : Operating cost of CCC *j* in period *t*

OC_t^{RC} : Operating cost of recycling facility in period *t*

Q_{it} : Quantity of used tires supply by ICA *i* in period *t*

TR_t : Transportation cost/ton, unit distance from ICAs to CCCs, from CCCs to recycling facility or retreading facilities in period *t*

TR_t^{CF} : Transportation cost/ton, unit distance from CCCs to cement facilities in period *t*

d_{ij}^{CCC} : Distance from ICA *i* to CCC *j*

d_{jl}^{RT} : Distance from CCC *j* to retreading facility *l*

d_j^{RC} : Distance from CCC *j* to recycling facility

d_{jm}^{CF} : Distance from CCC *j* to cement facility *m*

e_n : The rate of product *n* (in percentage) produced at recycling facility

h_{nt}^{RC} : Holding cost per ton per period for product *n* resulting from recycling in period *t*

D_{nt}^{RC} : Demand for product *n* produced in recycling facility in period *t*

Variables

V_{ijt}^{CCC} : Volume of tires sent from ICA *i* to CCC *j* in period *t*

V_{jlt}^{RT} : Volume of retreadable tires sent from CCC *j* to retreading facility *l* in period *t*

V_{jt}^{RC} : Volume of tires sent from CCC *j* to recycling facility in period *t*

V_{jmt}^{CF} : Volume of tires sent from CCC *j* to cement facility *m* in period *t*

V_{nt}^{RCP} : Volume of product *n* produced in recycling facility in period *t*

U_{nt}^{-} : Unsatisfied demand for product *n* at the end of period *t*

U_{nt}^{+} : Excess volume of product *n* at the end of period *t*

$$X_j = \begin{cases} 1 & \text{if CCC } j \text{ is opened} \\ 0 & \text{otherwise} \end{cases}$$

$$Y_l = \begin{cases} 1 & if \text{ retreading facility } l \text{ is opened} \\ 0 & \text{otherwise} \end{cases}$$

$$Z = \begin{cases} 1 & if \text{ recycling facility is operated} \\ 0 & \text{otherwise} \end{cases}$$

Objective Function

The objective is to find the optimal logistics network design that maximizes the overall profit for multi-period case by determining which facilities to open. The objective function consists of terms which represent total revenues and costs over the planning horizon. Compared to the objective function of the single-period model, the holding cost is considered additionally in this model. Moreover, variable costs that are unit retreading, operating, or transportation costs and sales revenues are considered for every time period. Salvage value of unsold product *n* is not considered in this model, because the unsold product *n* in a period is carried to the next period as inventory. A brief definition of the objective function is given below.

Expression (3.31) represents sales revenues that come from selling the retreaded tires, recycled products, or used tires to cement facilities. Expression (3.32) represents setup costs of establishing CCCs and retreading facilities. Expression (3.33) represents cost of retreading used tires. Since the unit production cost of recycling used tires is given in operating costs by the recycling company, total production costs of recycling used tires are included in operating costs. Expression (3.34) represents total operating costs of CCCs, retreading facilities and recycling facility. Expression (3.35) represents total transportation costs between operators of network. The additional Expression (3.36) represents the holding cost of recycled products.

A brief definition of the objective function can be shown as:

max z= Sales Revenues - (Setup Costs + Retreading Costs + Operating Costs +Transportation Costs + Holding Costs)

The mathematical formulation of the objective function is given below :

Sales Revenues:

$$\sum_t \sum_l \sum_j p_t^{RT} w V_{jlt}^{RT} \ + \sum_t \sum_n p_{nt}^{RC} (D_{nt}^{RC} - U_{nt}^{-}) + \sum_t \sum_m \sum_j p_t^{CF} V_{jmt}^{CF} \tag{3.31}$$

Setup Costs:

$$\sum_j S_j^{CCC} X_j \ + \sum_l S_l^{RT} Y_l \tag{3.32}$$

Retreading Costs:

$$\sum_t \sum_l \sum_j c_t^{RT} w V_{jl}^{RT} \tag{3.33}$$

Operating Costs:

$$\sum_t \sum_j OC_{jt}^{CCC} X_j \ + \sum_t \sum_j OC_{lt}^{RT} Y_l \ + \sum_t OC_t^{RC} Z \tag{3.34}$$

Transportation Costs:

$$\sum_t \sum_j \sum_i TR_t V_{ijt}^{CCC} d_{ij}^{CCC} + \sum_t \sum_l \sum_j TR_t V_{jlt}^{RT} \ d_{jl}^{RT} + \sum_t \sum_j TR_t V_{jt}^{RC} d_j^{RC} \ + \\ + \sum_t \sum_m \sum_j TR_t^{CF} V_{jmt}^{CF} d_{jm}^{CF} \tag{3.35}$$

Holding Cost :

$$\sum_t \sum_n h_{nt}^{RC} U_{nt}^{+} \tag{3.36}$$

Constraints

Expression (3.37) represents that the total volume of used tires sent from ICA *i* to CCC *j* is less than or equal to the used tire supply capacity of ICA *i* in period *t*.

$$\sum_j V_{ijt}^{CCC} \leq Q_{it} \ ; \ \forall i \in I \ and \ \forall t \in T \tag{3.37}$$

Expression (3.38) represents that the total volume of used tires sent from ICAs to CCC *j* cannot exceed the capacity of CCC *j* in period *t*.

$$\sum_i V_{ijt}^{CCC} \leq K_j^{CCC} X_j \ ; \forall j \in J \ \text{ and } \forall t \in T \tag{3.38}$$

Expression (3.39) indicates that the volume of used tires received by CCC *j* has to be sent one of three facilities which are retreading, recycling, or cement facilities. Therefore, this constraint makes sure that the incoming flow to each CCC *j* is equal to outgoing flow from each CCC *j* in period *t*.

$$\sum_i V_{ijt}^{CCC} = V_{jt}^{RC} + \sum_l V_{jlt}^{RT} + \sum_m V_{jmt}^{CF} \ , \ \forall j \in J \text{ and } \forall t \in T \tag{3.39}$$

At least one retreading facility is opened as shown by Expression (3.40).

$$\sum_l Y_l \geq 1 \tag{3.40}$$

A certain proportion of used tires that are collected from customers is retreadable. Expression (3.41) determines the retreadable tire volume received by CCC *j* considering the retreadable tire ratio *r* in period *t*.

$$\sum_l V_{jlt}^{RT} \leq \sum_i V_{ijt}^{CCC} r, \quad \forall j \in J \text{ and } \forall t \in T \tag{3.41}$$

Total volume of used tires sent from CCCs to retreading facility *l* cannot exceed the capacity of retreading facility *l* in period *t* as shown by Expression (3.42).

$$\sum_j w V_{jlt}^{RT} \leq K_l^{RT} Y_l \quad, \quad \forall l \in L \text{ and } \forall t \in T \tag{3.42}$$

Expression (3.43) represents the capacity constraint of recycling facility. In this equation, total volume of used tires sent from CCCs to the recycling facility cannot exceed the capacity of recycling facility in period *t*.

$$\sum_j V_{jt}^{RC} \leq K^{RC} Z \quad, \quad \forall t \in T \tag{3.43}$$

Expression (3.44) determines the volume of product *n* produced by recycling facility.

$$V_{nt}^{RCP} = e_n \sum_j V_{jt}^{RC}, \quad \forall n \in N \text{ and } \forall t \in T \tag{3.44}$$

Expression (3.45) represents the inventory balance constraint regarding product *n*. Customer demand for recycled product *n* can be met by either the volume produced in recycling facility in period *t* or the stock coming from previous period *t-1*.

$$U_{nt}^{+} - U_{nt}^{-} = U_{n,t-1}^{+} + V_{nt}^{RCP} - D_{nt}^{RC}, \quad \forall n \in N \text{ and } \forall t \in T \qquad (3.45)$$

4. NUMERICAL EXPERIMENTS

Single-period and multi-period models are solved using the modeling language GAMS 23.6. The GAMS codes for Model I and Model II for single period and multi-period cases are given in Appendix A, Appendix B, Appendix C and Appendix D respectively. The data collected for the model parameters from the recycling and retreading companies and the results for the two models are given in the following sections.

4.1. Parameters

A case study of a tire recycling company which is located in Sakarya, Turkey is considered in this study. Using the models formulated in chapter 3, the profitability of entering into the tire retreading business for this recycling company is investigated. The recycling company under consideration is authorized to collect the used tires in Marmara Region only, which is one of the eight geographical regions of Turkey. Hence the potential used tire supply points and customers who demand the products resulting from tire recovery in this region are considered. Each region of Turkey has different population size and industrial needs, thus the supply amount of used tires is different in different regions. Marmara region supplies 20%-25% of the total amount of used tires overall Turkey. There are hundreds of used tire supply points such as vehicle dealers, auto services, tire repair & maintenance shops etc. in Marmara region. For convenience, these supply points are grouped into Initial Collection Areas (ICAs), each representing one city in Marmara region. The supply amount of used tires at an ICA is equal to the total quantity of used tires received by these small shops that are located in the city represented by that ICA. The supply amount by each ICA is estimated based on the population and industry of the given city.

Turkish government determines a quota for the minimum amount of used tires to be collected and recovered in each year. This quota is determined considering the previous year's sales of tires. Thus, tire manufacturers are responsible of collecting at least a proportion of the previous year's tire sales. This proportion is increased by the government each year. For instance, while tire manufacturers were responsible to collect at least 30% of the amount of tires sold in 2007, they are responsible to collect at least 70% of the number of tires sold in 2013. From 2007 to 2012, the required minimum number of used tires collected is achieved. In Table 4.1, the quotas for tire collection and the amount of used tires collected overall Turkey and in Marmara Region only for years 2007 to 2012 are shown. The data in this table is provided by LASDER (Lastik Sanayicileri Derneği).

Table 4.1. Quotas and amounts of used tires collected for years 2007-2012

Year	Quota(%)	In Turkey (Eight Regions)	In Marmara Region
2007	30%	9850	2463
2008	35%	24200	6050
2009	40%	35552	8888
2010	45%	72400	18100
2011	50%	91700	22925
2012	60%	113000	32500

The predicted quotas and amount of used tires (tons) to be collected overall Turkey and in Marmara Region only is given in Table 4.2.

Table 4.2. Predicted quotas and amount of used tires collected for years 2013 and 2014

Year	Quota (%)	In Turkey (Eight Regions)	In Marmara Region
2013	70	130,000	32,500
2014	80	150,000	37,500

Marmara Region has 16 ICAs, each representing a city in this region. Different quantities of used tires are collected from each ICA due to the population and industrial sites of ICA. The estimated proportions for the used tires collected in each ICA in Marmara region with the corresponding quantities of used tires for years 2007-2012 are given in Table 4.3.

Table 4.3. Estimated Proportion (%) and amount of used tires (in tons) collected in each ICA for years 2007-2012

	Proportion (%)	2007	2008	2009	2010	2011	2012
Istanbul	16	395	968	1422	2896	3668	4520
Tekirdag	8	197	484	711	1448	1834	2260
Edirne	8	197	484	711	1448	1834	2260
Kirklareli	6	148	363	533	1086	1376	1695
Balikesir	6	148	363	533	1086	1376	1695
Bilecik	2	49	121	178	362	459	565
Bolu	4	99	242	355	724	917	1130
Bursa	10	246	605	889	1810	2293	2825
Canakkale	8	197	484	711	1448	1834	2260
Eskisehir	8	197	484	711	1448	1834	2260
Kocaeli	2	49	121	178	362	459	565
Kutahya	6	148	363	533	1086	1376	1695
Sakarya	4	99	242	355	724	917	1130
Zonguldak	8	197	484	711	1448	1834	2260
Yalova	2	49	121	178	362	459	565
Duzce	2	49	121	178	362	459	565

The proportion and quantities of used tires in each ICA predicted for years 2013 and 2014 are given in Table 4.4.

Table 4.4. Estimated Proportion(%) and amount of used tires (in tons) predicted to be collected in each ICA for years 2013 and 2014

	Proportion (%)	2013	2014
Istanbul	16	5200	6000
Tekirdag	8	2600	3000
Edirne	8	2600	3000
Kirklareli	6	1950	2250
Balikesir	6	1950	2250
Bilecik	2	650	750
Bolu	4	1300	1500
Bursa	10	3250	3750
Canakkale	8	2600	3000
Eskisehir	8	2600	3000
Kocaeli	2	650	750
Kutahya	6	1950	2250
Sakarya	4	1300	1500
Zonguldak	8	2600	3000
Yalova	2	650	750
Duzce	2	650	750

In the existing network, the recycling company is responsible to collect and recover used tires through either recycling or combustion in cement facilities for energy recovery. Distances between the ICAs and the recycling and cement facilities are given in Table 4.5 and Table 4.6.

Table 4.5. The distances between each ICA and recycling facility in km

	Distance in km
	Sakarya
Istanbul	158
Tekirdag	299
Edirne	393
Kirklareli	367
Balikesir	322
Bilecik	101
Bolu	126
Bursa	171
Canakkale	439
Eskisehir	178
Kocaeli	53
Kutahya	208
Sakarya	10
Zonguldak	196
Yalova	115
Duzce	81

In the proposed network, CCCs and retreading facilities are added to the existing network of the recycling company. There are five candidate locations for CCCs which are Catalca, Bolu, Sakarya, Yalova and Gebze, and three candidate locations for retreading facilities which are Sakarya, Gebze and Yalova. These locations are determined as potential locations for their closeness to the recycling facility and the density of the industry area.

Table 4.6. The distances between ICAs and cement facilities in km

	Distance (km)					
	Akcansa (Istanbul)	Akcansa (Canakkale)	Aslan Cimento (Kocaeli)	Bursa Cimento	Cimentas (Edirne)	Cimsa (Eskişehir)
Istanbul	30	550	100	239	257	324
Tekirdag	130	695	250	383	161	466
Edirne	220	786	341	474	25	559
Kirklareli	195	760	315	448	52	533
Balikesir	422	191	283	150	641	314
Bilecik	283	419	141	82	501	83
Bolu	303	598	162	102	519	292
Bursa	265	322	126	9	483	162
Canakkale	538	54	399	266	756	326
Eskisehir	360	477	218	159	578	430
Kocaeli	160	461	14	149	371	5
Kutahya	397	418	248	189	608	232
Sakarya	193	485	53	167	410	178
Zonguldak	379	507	230	352	590	362
Yalova	212	381	68	67	428	204
Duzce	265	554	115	237	476	247

Table 4.6.*(continued)* The distances between ICAs and cement facilities in km

	Distance (km)				
	Colakoglu (Kocaeli)	Kimtas (Kırklareli)	Nuh Beton (Kocaeli)	Oyak Cimento (Bolu)	Set Cimento (Balıkesir)
Istanbul	81	15	76	290	369
Tekirdag	224	89	255	433	529
Edirne	315	108	311	500	620
Kirklareli	289	31	285	475	571
Balikesir	318	571	312	436	6
Bilecik	178	431	172	215	253
Bolu	202	450	191	70	240
Bursa	160	413	154	283	156
Canakkale	433	686	428	552	227
Eskisehir	255	508	249	292	311
Kocaeli	47	301	41	174	295
Kutahya	285	538	279	322	225
Sakarya	93	341	82	189	277
Zonguldak	267	520	261	172	503
Yalova	111	358	100	287	173
Duzce	153	406	147	51	388

Recycling company is responsible of transporting the used tires from ICAs to CCCs and from CCCs to retreading, recycling or cement facilities. The distances between ICAs and CCCs, and between CCCs and retreading facilities are given in Table 4.7 and Table 4.8. The recycling facility is located in Sakarya, and the distances between the potential locations of CCCs, which are Catalca, Bolu, Sakarya, Yalova and Gebze, to recycling company are 231 km, 116 km, 0 km, 141 km and 124 km, respectively.

Table 4.7. The distances between each ICA and CCC in km

	Distance (km)				
	Catalca	Bolu	Sakarya	Yalova	Gebze
Istanbul	55	266	158	175	68
Tekirdag	106	408	299	316	210
Edirne	200	501	393	409	303
Kirklareli	174	475	367	383	277
Balikesir	440	436	322	216	333
Bilecik	298	215	101	109	191
Bolu	318	10	126	227	211
Bursa	285	285	171	60	178
Canakkale	550	553	439	332	450
Eskisehir	375	292	178	202	268
Kocaeli	167	161	53	69	53
Kutahya	405	322	208	233	298
Sakarya	210	126	10	119	102
Zonguldak	388	170	196	298	281
Yalova	226	223	115	7	119
Duzce	273	50	81	183	166

Table 4.8. The distances between each CCC and each retreading facility

	Distance(km)		
	Sakarya	Gebze	Yalova
Catalca	210	120	226
Bolu	126	211	227
Sakarya	0	92	109
Yalova	108	113	0
Gebze	102	0	112

Transportation cost is given per unit distance (km) and per unit volume (ton) of tires transported. Transporting used tires from CCCs to the cement facilities is considered to be more costly than transporting them from ICAs to CCCs or from CCCs to the recycling facility or the retreading facility. The transportation cost from CCCs to cement facilities is 1 TL/km/ton while the transportation cost for other cases is 0.75 TL/km/ton.

Non-retreadable used tires are sent to recycling company or cement facilities for energy recovery. There are 11 cement facilities to which the recycling company can sell the used tires in the Marmara Region, which are Akcansa, Aslan Cimento, Bursa Cimento, Cimentas, Cimsa, Colakoglu, Kimtas, Nuh Beton, Oyak Cimento, Set Cimento where locate in Istanbul, Canakkale, Kocaeli, Bursa, Edirne, Eskisehir, Kirklareli, Bolu and Balikesir, The distances between CCCs and cement facilities are given in Table 4.9. The used tires are sold to cement facilities at the price of 66 TL/ ton.

Table 4.9. The distances between CCCs and cement facilities

	Distances (km)					
	Akcansa (Istanbul)	Akcansa (Canakkale)	Aslan Cimento (Kocaeli)	Bursa Cimento	Cimentas (Edirne)	Cimsa (Eskişehir)
Catalca	17	604	157	290	219	376
Bolu	303	598	162	281	519	292
Sakarya	193	485	53	167	410	178
Yalova	212	381	68	67	428	203
Gebze	98	500	54	186	310	272

Table 4.9. *(continued)* The distances between CCCs and cement facilities

	Distances (km)				
	Colakoglu (Kocaeli)	Kimtas (Kırklareli)	Nuh Beton (Kocaeli)	Oyak Cimento (Bolu)	Set Cimento (Balıkesir)
Catalca	65	150	129	381	396
Bolu	202	450	191	70	240
Sakarya	93	341	82	189	277
Yalova	111	358	100	287	173
Gebze	20	241	25	278	55

Furthermore, when used tires are sent to recycling facility or retreading facilities, a unit recycling or retreading cost occurs per unit ton of used tires recycled or unit tire retreaded. The recycling company considers that the recycling cost is included in the overall operating cost, which is around 7,800,000 TL/ year for a facility with capacity of 20,000 tons of tires. After recycling, the main products obtained are granule and steel wire at respective rates of 65% and 25%. The unit selling price of these products and the annual holding costs per ton are given in Table 4.10.

Table 4.10. The proportion, unit selling price, and holding costs of products produced in recycling process

	Proportion (%)	Unit Selling Price (TL/Ton)	Holding Costs (TL/Ton)
Granule	65	400	90
Steel Wire	25	500	90

Demand for the recycled products may vary from year to year. Since the governmental regulations determine that scrap tires can be stocked at most 60 days, the recycling company prefers to recycle all used tires that are sent to the recycling facility instead of stocking them in their entire form. The actual and/or predicted demands for profucts resulting from recycling for years 2012-2013 are given in Table 4.11. The unsold products in the single-period case are sold to cement facilities for energy recovery at a price of 3 TL/ton.

Table 4.11. Demand for products resulting from recycling for years 2012-2014

	Demand for Recycled Products (Tons)		
	2012	2013	2014
Granule	6500	7500	8500
SteelWire	5500	6500	7500

The cost/price data regarding the tire retreading business are collected through visits to a tire retreading company. The retreading cost is 300 TL/unit tire while the unit selling price of a retread tire is 400-450 TL/unit tire. Setup and operating costs of the retreading facility depend on the capacity of the facility. Setup costs for 3-year base and operating costs of potential retreading facilities with corresponding capacities are given in the Table 4.12.

Table 4.12. Capacities, setup and operating costs of candidate retreading facilities

	Candidate Retreading Facility		
Candidate Location	Capacity (Unit Tire)	Setup Cost (TL)	Operating Cost (TL/Year)
Sakarya	72000	178271	711909
Gebze	48000	237694	517752
Yalova	24000	297118	280449

Similarly, each CCC also has setup and operating costs. In Table 4.13, setup costs for 3-year base and operating costs of CCCs with corresponding capacities are given.

Table 4.13. Capacities, setup and operating costs of candidate CCCs

	Candidate Centralized Collection Centers		
Candidate Location	Capacity (Unit Tire)	Setup Cost (TL)	Operating Cost (TL/Year)
Catalca	2600	70000	24000
Bolu	7800	100000	180000
Sakarya	13000	150000	300000
Yalova	4680	80000	48000
Gebze	10400	125000	204000

4.2. Analysis for Single-Period Case

Single-period model is solved considering year 2012 data. The profitability of the tire recovery is investigated for different retreadable tire ratio values, and the result of Model I (representing the actual network) is compared to the results of Model II (representing the proposed network). The optimal profit and locations for CCCs and retreading facilities to open corresponding to different scenarios are provided in Table 4.14.

Results show that the existing network for tire recovery, which consists of only recycling facility, makes a profit of around 4.7 million TL per period. When retreading process is added to the existing network, CCCs are required to open in addition to retreading facility. There are additional cost of setup and operating costs of retreading facilities and CCCs in the proposed network.

Table 4.14. Optimal solutions for different scenarios for single-period model

Optimal solution	Model I	Model II				
		Retreadable tire ratio				
		5%	6%	6.57%	7%	8%
Profit (million TL)	4.7	3.97	4.4	4.7	5	5.56
Additional profit	0%	-15.53%	-6.38%	0%	6.38%	18.30%
CCCs to open	-	Bolu, Sakarya, Yalova, Catalca, Gebze	Sakarya, Yalova, Catalca, Gebze	Sakarya, Yalova, Catalca, Gebze	Sakarya, Yalova, Catalca, Gebze	Sakarya, Yalova, Catalca, Gebze
Retreading facilities to open	-	Yalova	Yalova	Gebze	Gebze	Gebze

For different retreadable tire ratios, the differences in profit and facilities to open are observed. As can be seen from Table 4.14, when the retreadable tire ratio is less than 6.57%, the amount of retreadable tires are not enough to make the operating of retreading facilities more profitable than the actual case of recycling only. Therefore, it is less profitable for the company to enter into tire retreading business in a single-period. For the retreadable tire ratios of 5% and 6%, the company makes a loss of 15.53% and 6.38%, respectively compared to the actual situation.

If the retreadable tire ratio is greater than 6.57%, the company starts to make an additional profit. For instance, the additional profit is around 6% when the retreadable tire ratio is 7%, and it increases to 18% when the retreadable tire ratio is 8%. In this case, the breakeven point occurs at the retreadable tire ratio 6.57%.

4.3. Analysis for Multi-Period Case

The multi-period model is solved for years 2012 to 2014. The results show that in the three-year model, the existing tire recovery network makes a profit of around 8.2 million TL.

The proposed model for the logistics network with recycling & retreading processes is solved for different retreadable tire ratios and the breakeven point after which the remanufacturing business gets profitable is determined. The profit for the current network where the company does recycling only is compared to the profit of the proposed network where CCCs and retreading facilities are operated in addition to recycling facility. The optimal profit and locations for CCCs and retreading facility to open corresponding to different scenarios are provided in Table 4.15.

Table 4.15. Optimal solutions for different scenarios for multi-period model

Optimal solution	Model I	Model II Retreadable tire ratio 3%	3.3%	3.7%	4%	7%
Profit (million TL)	8.2	7.8	8.2	8.7	10	13.3
Additional profit	0%	-3.7%	0%	7.41%	21.25%	62.20%
CCCs to open	-	Sakarya, Catalca	Sakarya, Catalca	Sakarya, Yalova, Catalca	Sakarya, Yalova, Catalca, Gebze	Sakarya, Yalova, Catalca, Gebze
Retreading facilities to open	-	Yalova	Yalova	Yalova	Yalova	Yalova

For different retreadable tire ratios, the additional profits and the CCCs and retreading facility that are opened are observed. When the retreadable tire ratio is below 3.3%, it is less profitable for the company to enter into tire retreading business in multi-period case. If the retreadable tire ratio is greater than 3.3%, the company starts to make an additional profit. The additional profit is around 7.41%, 21.25%, 62.20% when the retreadable tire ratio is 3.7%, 4% and 7%, respectively. According to results, it can be assumed that the proposed network is more profitable in the long-term, and it makes profit even for very small retreadable tire ratios. As the volume of retreadable tires increases, the CCCs to open change considering their corresponding capacities. The model opens the most suitable CCCs and retreading facilities for the proposed network that maximizes the overall profit.

When Table 4.14 and Table 4.15 are compared, it can be seen that the retreading business for this company becomes profitable at a lower retreadable tire ratio (3.7%) compared to single-period case for which the breakeven point was 6.57%. From this observation, we can conclude that retreading facility would be more profitable in the long-term since the used tires supply amount and demand for resulting products tend to increase year after year due to increasing population.

5. CONCLUSION

In the existing logistics network for tire recovery in Turkey, the network consists of recycling and energy recovery options, thus, retreading process is not considered for the used tires collected back from users. Additionally, in Turkey, there is no company that do both tire retreading and recycling, i.e. recycling-only or retreading-only companies exist. We study the problem of designing a logistics network for a tire recycling company who considers doing also tire retreading.

The company does not currently have a tire retreading facility nor a centralized collection center (CCC) where tires coming from initial collection areas are inspected and sorted. In order to add the retreading process into the existing network, not only retreading facilities need to be open, but also centralized collection centers (CCCs) need to be open, because the tires coming from each initial collection area (ICA) are required to be inspected for their quality condition and sorted. After sorting, the retreadable tires are sent to retreading facilities and the remaining tires are considered for recycling or energy recovery.

In order to determine the profitability of tire recovery (both recycling and retreading), a logistics network design problem is formulated as a mixed integer linear program. First, the model is formulated for the single-period case and then it is extended to multi-period case. Both models determine where to locate CCCs and retreading facilities to maximize the overall profit of the company.

A numerical experimentation is done, where the models are solved for different scenarios corresponding to different values of retreadable tire ratio in order to see the effects on the optimal profit and design of the network, and the results are compared to current situation for the company. In single-period multi-product model, results show that tire retreading increases the profit when retreadable tire ratio at least 6.57% compared to doing only recycling.

In the multi-period model, results show that tire retreading increases the profit by at least 7.41% compared to doing only recycling when the retreadable tire ratio is at least 3.7%. .Additionally, it is seen that the company reaches the breakeven point at a lower retreadable ratio value, which is 3.3%, compared to single-period case. Hence, it can be said that the proposed model makes profit for the company in the long-term since the used tires supply amount and demand for resulting products tend to increase year after year due to increasing population.

As further study, the problem of tire recovery can be extended to cover all eight regions of Turkey in order to determine the economic value of tire recovery network over the country. However, this case may result in large-scale model. If the size of the resulting model is too large to be solved to optimality in a reasonable amount of time, development of a fast heuristic methodology that finds high-quality solutions is of interest.

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APPENDIX A : MODEL I FOR SINGLE-PERIOD MODEL

```
sets
       i ICP /Istanbul,
              Tekirdag,
              Edirne,
              Kirklareli,
              Balikesir,
              Bilecik,
              Bolu,
              Bursa,
              Canakkale,
              Eskisehir,
              Kocaeli,
              Kutahya,
              Sakarya,
              Zonguldak,
              Yalova,
              Duzce/
       j CRC
             /Catalca,
              Bolu,
              Sakarya,
              Yalova,
              Gebze/
       l retreading facility /Sakarya, Gebze, Yalova/

      m cement facility /AkcansaISt, AkcansaCank, AslanKoc, BursaCim, CimentasEdr,
CimsaEsk, ColakogluKoc, KimtasKirk, NuhKoc, OyakBolu, SetCimBal/

      n product recycled in recycling facility /Granule, SteelWire/
;

scalars
      r    retreadable tire ratio
      pCF  selling price per ton of scrap tires to cement facility
      oRC  operating cost of recycling facility
      kRC  capacity of recycling facility l
      trR  transportation cost to recycling per unit per km
      trCF transportation cost to cement facility per unit per km
      sv salvage value
;
```

```
pCF=66;
oRC=780000;
kRC=20000;
trR=0.75;
trCF=1;
sv=3;

parameters

        e(n)    proportion of product n recycled in recycling facility
        / Granule   0.65
          SteelWire 0.25 /

        pRC(n)  unit selling price of product n recycled (TL\ton)
        / Granule      400
          SteelWire   500
        /

        dRC(i) distance from ICP i to recycling facility (km)
           / Istanbul          158
             Tekirdag         299
             Edirne            393
             Kirklareli       367
             Balikesir        322
             Bilecik           101
             Bolu              126
             Bursa             171
             Canakkale        439
             Eskisehir        178
             Kocaeli            53
             Kutahya          208
             Sakarya            10
             Zonguldak        196
             Yalova           115
             Duzce              81 /

;

parameter q(i) quantity of used tires received to ICP i
/
Istanbul        4520
Tekirdag       2260
Edirne          2260
Kirklareli     1695
Balikesir      1695
Bilecik          565
Bolu            1130
Bursa           2825
```

```
Canakkale    2260
Eskisehir    2260
Kocaeli       565
Kutahya      1695
Sakarya      1130
Zonguldak    2260
Yalova        565
Duzce         565
/;

parameter dmRC(n) demand for recycled product n
/
Granule     20000
SteelWire   10000
/;

table dCF(j,m)  distance from CRC j to cement facility m (km)

             AkcansaISt  AkcansaCank  AslanKoc  BursaCim  CimentasEdr  CimsaEsk
Istanbul         30          550         100       240        257         324
Tekirdag        130          695         250       383        161         466
Edirne          220          786         341       474         25         559
Kirklareli      195          760         315       448         52         533
Balikesir       422          191         283       150        641         314
Bilecik         283          419         141        82        501          83
Bolu            303          598         162       281        519         292
Bursa           265          322         126       146        483         162
Canakkale       538           54         399       266        756         326
Eskisehir       360          477         218       159        578         430
Kocaeli         160          461          14       149        371           5
Kutahya         397          418         248       189        608         232
Sakarya         193          485          53       167        410         178
Zonguldak       379          507         230       352        590         362
Yalova          212          381          68        67        428         204
Duzce           265          554         115       237        476         247
 ;

variables
      z total profit(net revenue);

positive variables
      vRC(i)    volume of recyclable tire transported from CRC j to recycling facility in
period t
      vCF(i,m)  volume of retreaded tire transported from CRC j to cement facility m in
period t
      vRCP(n)   volume of resource n produced in recycling facility in period t
      Un(n)    non-satisfied volume of product n recycled in recycling facility in period t
      Up(n)     excess volume of product n recycled in recycling facility in period
```

```
binary variables
        w    if recycling facility is operated
        ;

equations
obj objective function
cons1(i)
cons2
cons3(n)
cons4(n)
;

obj.. z=e= sum(n,(dmRC(n)-
Un(n))*pRC(n))+sum(n,Up(n)*sv)+sum((i,m),vCF(i,m)*pCF)-
(oRC*w+sum(i,vRC(i)*dRC(i)*trR)+sum((i,m),vCF(i,m)*dCF(i,m)*trCF));

cons1(i).. vRC(i)+sum(m,vCF(i,m))=l= q(i) ;
cons2..    sum(i,vRC(i))=l=kRC*w;
cons3(n).. vRCP(n)=e=sum(i,vRC(i)*e(n));
cons4(n).. Up(n)-Un(n)=e=vRCP(n)-dmRC(n);

model   tire /all/;
solve   tire using mip maximizing z;
display z.l,vRC.l,vRCP.l,vCF.l,Un.l,Up.l;
```

APPENDIX B : MODEL I FOR MULTI-PERIOD MODEL

```
sets
        i ICP /Istanbul,
              Tekirdag,
              Edirne,
              Kirklareli,
              Balikesir,
              Bilecik,
              Bolu,
              Bursa,
              Canakkale,
              Eskisehir,
              Kocaeli,
              Kutahya,
              Sakarya,
              Zonguldak,
              Yalova,
              Duzce/

        m cement facility /AkcansaISt, AkcansaCank, AslanKoc, BursaCim,
CimentasEdr, CimsaEsk, ColakogluKoc, KimtasKirk, NuhKoc, OyakBolu, SetCimBal/

        n product recycled in recycling facility /Granule, SteelWire/

        t time horizon /2012,2013,2014/
;

scalars

       kRC capacity of recycling facility l
;

kRC=20000;

parameters

         sv(t) salvage value of products
        /
         2012 3
         2013 3.3
         2014 3.63 /
```

```
  e(n) proportion of product n recycled in recycling facility
 / Granule   0.65
   SteelWire 0.25 /

 pCF(t) selling price per ton of scrap tires to cement facility
 / 2012  66
   2013  72
   2014  79
 /

 oRC(t) operating cost of recycling facility
 / 2012  780000
   2013  858000
   2014  943800
 /
 trR(t)  transportation cost to recycling per unit per km
 / 2012 0.75
   2013 0.825
   2014 0.9075
 /

 trCF(t) transportation cost to cement facility per unit per km
 / 2012   1
   2013   1.1
   2014   1.21
 /
;

table pRC(n,t)  unit selling price of product n recycled (TL\ton)
              2012   2013   2014
Granule       400    440    484
SteelWire     500    550    605
;
table q(i,t) quantity of used tires received to ICP i in each period (Ton)
                2012     2013    2014
Istanbul        4520     5200    6000
Tekirdag        2260     2600    3000
Edirne          2260     2600    3000
Kirklareli      1695     1950    2250
Balikesir       1695     1950    2250
Bilecik          565      650     750
Bolu            1130     1300    1500
Bursa           2825     3250    3750
Canakkale       2260     2600    3000
Eskisehir       2260     2600    3000
Kocaeli          565      650     750
Kutahya         1695     1950    2250
Sakarya         1130     1300    1500
```

```
Zonguldak      2260     2600    3000
Yalova           565       650      750
Duzce            565       650      750;
table dmRC(n,t) demand for product n recycled in recycling facility (ton)
              2012    2013    2014
Granule      6500    7500    8500
SteelWire    5500    6500    7500
;

table hRC(n,t)  unit holding cost of product n in recycling facility (TL\ton)
             2012  2013  2014
Granule      90     99     108
SteelWire    90     99     108
;
parameter dRC(i) distance from ICP i to recycling facility (km)
         /
Istanbul         158
Tekirdag         299
Edirne           393
Kirklareli       367
Balikesir        322
Bilecik          101
Bolu             126
Bursa            171
Canakkale        439
Eskisehir        178
Kocaeli           53
Kutahya          208
Sakarya           10
Zonguldak        196
Yalova           115
Duzce             81
/;

table dCF(j,m)  distance from CRC j to cement facility m (km)

             AkcansaISt  AkcansaCank  AslanKoc  BursaCim  CimentasEdr  CimsaEsk
Istanbul       30           550         100       240        257          324
Tekirdag      130           695         250       383        161          466
Edirne        220           786         341       474         25          559
Kirklareli    195           760         315       448         52          533
Balikesir     422           191         283       150        641          314
Bilecik       283           419         141        82        501           83
Bolu          303           598         162       281        519          292
Bursa         265           322         126       146        483          162
Canakkale     538            54         399       266        756          326
Eskisehir     360           477         218       159        578          430
Kocaeli       160           461          14       149        371            5
```

```
Kutahya      397          418      248      189      608      232
Sakarya      193          485       53      167      410      178
Zonguldak    379          507      230      352      590      362
Yalova       212          381       68       67      428      204
Duzce        265          554      115      237      476      247
 ;

variables
        z total profit(net revenue);

positive variables
        vRC(i,t)    volume of recyclable tire transported from ICP i to recycling facility in
period t
        vCF(i,m,t)  volume of retreaded tire transported from ICP i to cement facility m in
period t
        vRCP(n,t)   volume of resource n produced in recycling facility in period t
        Un(n,t)     non-satisfied volume of product n recycled in recycling facility in
period t
        Up(n,t)     excess volume of product n recycled in recycling facility in period t
;
binary variables
w if recycling is operated;

equations
obj objective function
cons1(i,t)
cons2(t)
cons3(n,t)
cons4(n,t)
cons5(n)
;

obj.. z=e= sum((n,t),(dmRC(n,t)-
Un(n,t))*pRC(n,t))+sum((n,t),Up(n,t)*sv(t))+sum((i,m,t),vCF(i,m,t)*pCF(t))-
(sum(t,oRC(t)*w)
+sum((i,t),vRC(i,t)*dRC(i)*trR(t))+sum((i,m,t),vCF(i,m,t)*dCF(i,m)*trCF(t))+sum((n,t
),hRC(n,t)*Up(n,t)));

cons1(i,t).. vRC(i,t)+sum(m,vCF(i,m,t))=e= q(i,t) ;

cons2(t)..   sum(i,vRC(i,t))=l=kRC*w;

cons3(n,t).. vRCP(n,t)=l=e(n)*sum(i,vRC(i,t));

cons4(n,t)$(ord(t)>1).. Up(n,t)-Un(n,t)=e=Up(n,t-1)-Un(n,t-1)+vRCP(n,t)-dmRC(n,t);

cons5(n).. Up(n,'2012')-Un(n,'2012')=e=vRCP(n,'2012')-dmRC(n,'2012');
```

```
model   tire /all/;
solve   tire using mip maximizing z;
display z.l,vRC.l,vRCP.l,vCF.l,Un.l,Up.l;
```

APPENDIX C : MODEL II FOR SINGLE-PERIOD MODEL

```
sets
        i ICP /
                Istanbul,
                Tekirdag,
                Edirne,
                Kirklareli,
                Balikesir,
                Bilecik,
                Bolu,
                Bursa,
                Canakkale,
                Eskisehir,
                Kocaeli,
                Kutahya,
                Sakarya,
                Zonguldak,
                Yalova,
                Duzce /

        j CRC /
                Catalca,
                Bolu,
                Sakarya,
                Yalova,
                Gebze /

        l retreading facility / Sakarya, Gebze, Yalova /

        m cement facility / AkcansaISt, AkcansaCank, AslanKoc, BursaCim,
                            CimentasEdr, CimsaEsk, ColakogluKoc, KimtasKirk,
                            NuhKoc, OyakBolu, SetCimBal /

        n product recycled in recycling facility / Granule, SteelWire /
;

scalars
        r       retreadable tire ratio
        cRT  unit retreading cost
```

```
        pRT  unit selling price of retreaded tire
        pCF  selling price per ton of scrap tires to cement facility
        oRC  operating cost of recycling facility
        kRC  capacity of recycling facility l
        trR    transportation cost to recycling-retreading per unit per km
        trCF  transportation cost to cement facility per unit per km
        coef  coefficient for converting tons to unit tire
;

coef=16;

r=0.14;

pRT=425;

cRT=300;

pCF=66;

oRC=780000;

kRC=20000;

trR=0.75;

trCF=1;

parameters

         kCRC(j) capacity of CRC j (TON Lastik\YEAR)

         / Catalca    2600
           Bolu        7800
           Sakarya   13000
           Yalova     4680
           Gebze      10400
         /

         kRT(l)  capacity of retread facility l  (Birim lastik\Yil)

         / Sakarya   72000
           Gebze      48000
           Yalova     24000
         /
```

```
sCRC(j) setup cost of opening CRC j (TL)
/ Catalca    70000
  Bolu       100000
  Sakarya   150000
  Yalova     80000
  Gebze      125000 /

sRT(l)  setup cost of opening retreading facility l (TL)

/ Sakarya   223229
  Gebze     178583
  Yalova    133937         /

oCRC(j) operating cost of CRC j (TL\year)

/ Catalca      24000
  Bolu         180000
  Sakarya      300000
  Yalova       48000
  Gebze        204000
/

oRT(l)  operating cost of retreading facility (TL\year)

/ Sakarya      711909
  Gebze        517752
  Yalova       280449
/

e(n)    proportion of product n recycled in recycling facility

/ Granule      0.65
  SteelWire   0.25
/

pRC(n)  unit selling price of product n recycled (TL\ton)

/ Granule     400
  SteelWire  500
/
dRC(j)  distance from CRC j to recycling facility (km)

/ Catalca      231
  Bolu         116
  Sakarya      0
  Yalova       141
  Gebze        124 / ;
```

```
parameter q(i) quantity of used tires received to ICP i

/
Istanbul      4520
Tekirdag      2260
Edirne        2260
Kirklareli    1695
Balikesir     1695
Bilecik       565
Bolu          1130
Bursa         2825
Canakkale     2260
Eskisehir     2260
Kocaeli       565
Kutahya       1695
Sakarya       1130
Zonguldak     2260
Yalova        565
Duzce         565
/ ;

parameter dmRC(n) demand for recycled product
/
Granule     20000
SteelWire   10000
/ ;

table dCRC(i,j) distance from ICP i to CRC j(km)

              Catalca   Bolu   Sakarya   Yalova   Gebze
Istanbul      55        266    158       175      68
Tekirdag      106       408    299       316      210
Edirne        200       501    393       409      303
Kirklareli    174       475    367       383      277
Balikesir     440       436    322       216      333
Bilecik       298       215    101       109      191
Bolu          318       10     126       227      211
Bursa         285       285    171       60       178
Canakkale     550       553    439       332      450
Eskisehir     375       292    178       202      268
Kocaeli       167       161    53        69       53
Kutahya       405       322    208       233      298
Sakarya       210       126    10        119      102
Zonguldak     388       170    196       298      281
Yalova        226       223    115       7        119
Duzce         273       50     81        183      166 ;
```

table dRT(j,l) distance from CRC j to retread facility l (km)

	Sakarya	Gebze	Yalova
Catalca	210	120	226
Bolu	126	211	227
Sakarya	0	92	109
Yalova	108	113	0
Gebze	102	0	112

;

table dCF(j,m) distance from CRC j to cement facility m (km)

	AkcansaISt	AkcansaCank	AslanKoc	BursaCim	CimentasEdr	CimsaEsk
Catalca	17	604	157	290	219	376
Bolu	303	598	162	281	519	292
Sakarya	193	485	53	167	410	178
Yalova	212	381	68	67	428	203
Gebze	98	500	54	186	310	272 ;

variables

z total profit(net revenue);

positive variables

vCRC(i,j) volume of used tire transported from ICP i to CRC j in period t

vRT(j,l) volume of retreadable tire transported from CRC j to retread facility l in period t

vRC(j) volume of recyclable tire transported from CRC j to recycling facility in period t

vCF(j,m) volume of retreaded tire transported from CRC j to cement facility m in period t

vRCP(n) volume of resource n produced in recycling facility in period t

Un(n) non-satisfied volume of product n recycled in recycling facility in period t

Up(n) excess volume of product n recycled in recycling facility in period t

binary variables

x(j) if CRC j is opened

y(l) if retread facility l is opened

```
    w   if recycling facility is operated ;

equations

obj objective function

cons1(i)
cons2(j)
cons3(j)
cons4(j)
cons5(l)
cons6
cons7(n)
cons8(n)
cons9;

obj..  z  =e=  sum((j,l),vRT(j,l)*pRT*coef)  +  sum(n,(dmRC(n)-Un(n))*pRC(n))  +
sum((j,m),vCF(j,m)*pCF)  -  (sum((j,l),cRT*coef*vRT(j,l))  +  sum(j,oCRC(j)*x(j))  +
sum(l,oRT(l)*y(l))  +  oRC*w  +  sum((i,j),vCRC(i,j)*dCRC(i,j)*trR)  +
sum((j,l),vRT(j,l)*dRT(j,l)*trR)  +  sum(j,vRC(j)*dRC(j)*trR)  +
sum((j,m),vCF(j,m)*dCF(j,m)*trCF) + sum(j,sCRC(j)*x(j)) + sum(l,sRT(l)*y(l))) ;

cons1(i).. sum(j,vCRC(i,j)) =e= q(i);

cons2(j).. sum(i,vCRC(i,j)) =l= kCRC(j)*x(j);

cons3(j).. sum(i,vCRC(i,j)) =e= vRC(j) + sum(l,vRT(j,l)) + sum(m,vCF(j,m));

cons4(j).. sum(l,vRT(j,l)) =l= sum(i,vCRC(i,j)*r);

cons5(l).. sum(j,vRT(j,l)*coef)=l= kRT(l)*y(l);

cons6..   sum(j,vRC(j)) =l= kRC*w;

cons7(n).. vRCP(n) =l= e(n)*sum(j,vRC(j));

cons8(n).. Up(n) - Un(n) =e= vRCP(n) - dmRC(n);

cons9.. sum(l,y(l))=g=1;
model   tire /all/;
solve   tire using mip maximizing z;
```

APPENDIX D : MODEL II FOR MULTI-PERIOD MODEL

```
sets
        i ICP /
                Istanbul,
                Tekirdag,
                Edirne,
                Kirklareli,
                Balikesir,
                Bilecik,
                Bolu,
                Bursa,
                Canakkale,
                Eskisehir,
                Kocaeli,
                Kutahya,
                Sakarya,
                Zonguldak,
                Yalova,
                Duzce /

         j CRC /
                Catalca,
                Bolu,
                Sakarya,
                Yalova,
                Gebze
                /

        l retreading facility / Sakarya, Gebze, Yalova /

        m cement facility / AkcansaISt, AkcansaCank, AslanKoc, BursaCim,
                            CimentasEdr, CimsaEsk, ColakogluKoc, KimtasKirk,
                            NuhKoc, OyakBolu, SetCimBal /

        n product recycled in recycling facility / Granule, SteelWire /

        t time horizon / 2012,2013,2014 /
;
```

```
scalars
        r   retreadable tire ratio

        kRC capacity of recycling facility l

        coef Coefficient for converting tons to unit tire
;

coef=16;

r=0.10;

kRC=20000;

parameters

          pCF(t) selling price per ton of scrap tires to cement facility

          /  2012  66
             2013  72
             2014  79
          /

         oRC(t) operating cost of recycling facility

          /  2012  780000
             2013  858000
             2014  943800
          /

         trR(t)  transportation cost to recycling-retreading per unit per km

          /  2012 0.75
             2013 0.825
             2014 0.9075
          /

         trCF(t) transportation cost to cement facility per unit per km

          /  2012 1
             2013 1.1
             2014 1.21
          /
```

```
kCRC(j) capacity of CRC j (TON Lastik\YEAR)
/ Catalca     2600
  Bolu        7800
  Sakarya    13000
  Yalova      4680
  Gebze      10400
/

kRT(l)  capacity of retread facility l  (Birim lastik\Yil)

/ Sakarya   72000
  Gebze     48000
  Yalova    24000
/

sCRC(j) setup cost of opening CRC j (TL)

/  Catalca   70000
   Bolu     100000
   Sakarya  150000
   Yalova    80000
   Gebze    125000
/

sRT(l)  setup cost of opening retreading facility l (TL)

/  Sakarya  178271
   Gebze    237694
   Yalova   297118

/

e(n)    proportion of product n recycled in recycling facility

/  Granule    0.65
   SteelWire 0.25 /

dRC(j)  distance from CRC j to recycling facility (km)

/  Catalca    231
   Bolu       116
   Sakarya    0
   Yalova     141
   Gebze      124
/
```

```
         pRT(t) unit selling price of retreaded tire in period t

         / 2012  425
           2013  467.5
           2014  514.25 /
        cRT(t) unit retreading price in period t

         /  2012  300
            2013  330
            2014  363
         /
;

table pRC(n,t)  unit selling price of product n recycled (TL\ton)

                  2012   2013   2014
Granule     400     440     484
SteelWire  500     550     605
;

table dmRC(n,t) demand for product n recycled in recycling facility (ton)

                     2012    2013    2014
Granule          6500    7500    8500
SteelWire      5500    6500    7500
;

table hRC(n,t)  unit holding cost of product n in recycling facility (TL\ton)

                  2012  2013  2014
Granule     90       99       108
SteelWire  90       99       108
;

table  oRT(l,t)  operating cost of retreading facility (TL\year)

                   2012        2013            2014
Sakarya      711909     783099.9     861409.9
Gebze         517752     569527.2     626479.9
Yalova        280449     308493.9     339343.3
;
```

table oCRC(j,t) operating cost of CRC j (TL\year)

	2012	2013	2014
Catalca	24000	26400	29040
Bolu	180000	198000	217800
Sakarya	300000	330000	363000
Yalova	48000	52800	58080
Gebze	204000	224400	246840

;

table q(i,t) quantity of used tires received to ICP i in each period (Ton)

	2012	2013	2014
Istanbul	4520	5200	6000
Tekirdag	2260	2600	3000
Edirne	2260	2600	3000
Kirklareli	1695	1950	2250
Balikesir	1695	1950	2250
Bilecik	565	650	750
Bolu	1130	1300	1500
Bursa	2825	3250	3750
Canakkale	2260	2600	3000
Eskisehir	2260	2600	3000
Kocaeli	565	650	750
Kutahya	1695	1950	2250
Sakarya	1130	1300	1500
Zonguldak	2260	2600	3000
Yalova	565	650	750
Duzce	565	650	750

;

table dCRC(i,j) distance from ICP i to CRC j(km)

	Catalca	Bolu	Sakarya	Yalova	Gebze
Istanbul	55	266	158	175	68
Tekirdag	106	408	299	316	210
Edirne	200	501	393	409	303
Kirklareli	174	475	367	383	277
Balikesir	440	436	322	216	333
Bilecik	298	215	101	109	191
Bolu	318	10	126	227	211
Bursa	285	285	171	60	178
Canakkale	550	553	439	332	450
Eskisehir	375	292	178	202	268
Kocaeli	167	161	53	69	53
Kutahya	405	322	208	233	298
Sakarya	210	126	10	119	102

```
Zonguldak    388     170     196        298     281
Yalova       226     223     115        7       119
Duzce        273     50      81         183     166
;

table dRT(j,l)  distance from CRC j to retread facility l (km)
                Sakarya   Gebze   Yalova
Catalca         210       120     226
Bolu            126       211     227
Sakarya         0         92      109
Yalova          108       113     0
Gebze           102       0       112 ;

table dCF(j,m)  distance from CRC j to cement facility m (km)

             AkcansaISt  AkcansaCank  AslanKoc  BursaCim  CimentasEdr  CimsaEsk
Catalca      17          604          157       290       219          376
Bolu         303         598          162       281       519          292
Sakarya      193         485          53        167       410          178
Yalova       212         381          68        67        428          203
Gebze        98          500          54        186       310          272     ;


variables
        z total profit(net revenue);

positive variables

        vCRC(i,j,t) volume of used tire transported from ICP i to CRC j in period t

        vRT(j,l,t)   volume of retreadable tire transported from CRC j to retread facility l
                     in period t

        vRC(j,t)     volume of recyclable tire transported from CRC j to recycling facility
                     in period t

        vCF(j,m,t) volume of retreaded tire transported from CRC j to cement facility m
                     in period t

        vRCP(n,t)  volume of resource n produced in recycling facility in period t

        Un(n,t)      non-satisfied volume of product n recycled in recycling facility in
                     period t

        Up(n,t)     excess volume of product n recycled in recycling facility in period t

binary variables
```

```
        x(j) if CRC j is opened

        y(l) if retread facility l is opened

        w is recycling facility is operated ;

equations

obj objective function

cons1(i,t)

cons2(j,t)

cons3(j,t)

cons4(j,t)

cons5(l,t)

cons6(t)

cons7(n,t)

cons8(n,t)

cons9(n)

cons10;

obj.. z =e= sum((j,l,t),vRT(j,l,t)*pRT(t)*coef) + sum((n,t),(dmRC(n,t) -
Un(n,t))*pRC(n,t)) + sum((j,m,t),vCF(j,m,t)*pCF(t)) -
(sum((j,l,t),cRT(t)*coef*vRT(j,l,t)) + sum((j,t),oCRC(j,t)*x(j)) + sum((l,t),oRT(l,t)*y(l))
+ sum(t,oRC(t)*w) + sum((i,j,t),vCRC(i,j,t)*dCRC(i,j)*trR(t)) +
sum((j,l,t),vRT(j,l,t)*dRT(j,l)*trR(t) + sum((j,t),vRC(j,t)*dRC(j)*trR(t)) +
sum((j,m,t),vCF(j,m,t)*dCF(j,m)*trCF(t)) + sum((n,t),hRC(n,t)*Up(n,t)) +
sum(j,sCRC(j)*x(j))+sum(l,sRT(l)*y(l)));

cons1(i,t).. sum(j,vCRC(i,j,t)) =l= q(i,t) ;

cons2(j,t).. sum(i,vCRC(i,j,t)) =l= kCRC(j)*x(j);

cons3(j,t).. sum(i,vCRC(i,j,t)) =e= vRC(j,t) + sum(l,vRT(j,l,t)) + sum(m,vCF(j,m,t));

cons4(j,t).. sum(l,vRT(j,l,t)) =l= sum(i,vCRC(i,j,t)*r);

cons5(l,t).. sum(j,vRT(j,l,t)*coef) =l= kRT(l)*y(l);
cons6(t).. sum(j,vRC(j,t)) =l= kRC*w;
```

```
cons7(n,t).. vRCP(n,t) =l= e(n)*sum(j,vRC(j,t));

cons8(n,t)$(ord(t)>1).. Up(n,t)-Un(n,t) =e= Up(n,t-1)-Un(n,t-1) + vRCP(n,t)-dmRC(n,t);

cons9(n).. Up(n,'2012')-Un(n,'2012') =e= vRCP(n,'2012') - dmRC(n,'2012');

cons10.. sum(l,y(l))=g=1;

model   tire /all/;
solve   tire using mip maximizing z;
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BIOGRAPHICAL SKETCH

Özden TOZANLI who was born in Beyoğlu in 1988, is a graduate student who recently studies her M.S. in Industrial Engineering at the Galatasaray University and works as Research and Teaching Assistant at Istanbul Kultur University. She graduated from Eyup Anatolian High School with 4,80 of GPA up to 5. Her B.S. degree is in Industrial Engineering, and she was graduated from Istanbul Kultur University with a second honor degree in 2011. She has 2 international Proceedings.