İSTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL OF SCIENCE ENGINEERING AND TECHNOLOGY

A CLOSED LOOP SUSTAINABLE SUPPLY CHAIN NETWORK DESIGN FOR WASTE ELECTRICAL & ELECTRONIC EQUIPMENT

M.Sc. THESIS

Gökhan ALDEMİR

Department of Management Engineering

Management Engineering Programme

Thesis Advisor: Assoc. Prof. Hür Bersam BOLAT

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İSTANBUL TEKNİK ÜNİVERSİTESİ ★ FEN BİLİMLERİ ENSTİTÜSÜ

ELEKTRİK VE ELEKTRONİK EKİPMAN ATIKLARI İÇİN KAPALI DÖNGÜ SÜRDÜRÜLEBİLİR TEDARİK ZİNCİRİ AĞ TASARIMI

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Gökhan ALDEMİR, a M.Sc. student of İTU Graduate School of Science Engineering and Technology student ID 507131012, successfully defended the thesis entitled "A CLOSED LOOP SUSTAINABLE SUPPLY CHAIN NETWORK DESIGN FOR WASTE ELECTRICAL & ELECTRONIC EQUIPMENT", which he prepared after fulfilling the requirements specified in the associated legislations, before the jury whose signatures are below.

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Date of Submission : 2 May 2016
Date of Defense : 8 Jun 2016

To my family,

FOREWORD

I would like to thank my advisor Assoc. Prof. Hür Bersam BOLAT for giving me valuable advice and support always when needed. I would also like to thank Assoc. Prof. Dilay ÇELEBİ for giving me valuable advice during my thesis study. Other important people considering my thesis is my room mate Tuğçe BELDEK, Setenay GÜRÇEŞME and Dudu BİLGİÇ whom I like to give my thanks for giving me support and motivation. Lastly I would like to thank to my parents Hatice ALDEMİR and Kemal ALDEMİR that they make me come to these days.

I hope the thesis "A MULTI PERIOD SUSTAINABLE SUPPLY CHAIN NETWORK DESIGN FOR WASTE ELECTRICAL & ELECTRONIC EQUIPMENT" which I wrote with high attention and effort will be beneficial for everyone who reads.

May 2016

Gökhan ALDEMİR
(Industrial Engineer)

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ABBREVIATIONS

CLSC	**:** Closed Loop Supply Chain
CLSCM	**:** Closed Loop Supply Chain Management
CLSC-ND	**:** Closed Loop Supply Chain Network Design
EU	**:** European Union
GHG	**:** Green-house Gas
MILP	**:** Mixed Integer Linear Programming
MPS	**:** Master Production Schedule
R&D	**:** Research and Development
RL	**:** Reverse Logistics
SCM	**:** Supply Chain Management
SSCM	**:** Sustainable Supply Chain Management
SSC-ND	**:** Sustainable Supply Chain Network Design
TBL	**:** Triple Bottom Line
UN	**:** United Nations
WEEE	**:** Waste Electrical and Electronic Equipment

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A CLOSED LOOP REVERSE SUPPLY CHAIN NETWORK DESIGN FOR WASTE ELECTRICAL & ELECTRONIC EQUIPMENT

SUMMARY

Supply Chain Management covers the management of all activities starting from the supply of the raw material to the delivery of the final product to the end user. In the rapidly evolving and globalizing world, limited resources and increasing competitiveness push both the nations and the organizations to make difference in the context of supply chain management. Since the carbon dioxide emissions is one of the major causes of global warming mostly made by people, the importance of the concept of the sustainability is recently realised more among the nations and the organisations.

The topic of sustainable development has gained importance in many different fields, such as sustainable municipality, sustainable agriculture, sustainable architecture, sustainable production etc. There are negative effects from many factors such as solid waste, chemicals mixed with water, gases which are produced by manufacturing facility activities which have been neglected for many years.

Recovery options are considered to be an economic gain by a lot of companies. Moreover, pricing is no longer a unique competitive strategy since customers give today value and prefer environmentally friendly products. In other words, recovery options are considered by manufacturers due to customer demand, regulations and economical return.

This study puts forward a sustainable multi-period supply chain network design for minimize the waste of electric and electrical equipment which is the one of the most crucial sectors in terms of waste management. The contribution of this study is to fill the gap about the mathematical closed loop reverse supply chain network design model in multi-product, multi-objective and multi-period aspects for all of three dimensions of sustainability for decision making.

The proposed model is optimized with Mixed Integer Linear Programming. It is applied with a sample data set and sensitivity analysis is done with crucial decision variables. The study ends with future directions which gives some beneficial recommendations for other researchers on this topic.

ELEKTRİK VE ELEKTRONİK EKİPMAN ATIKLARI İÇİN KAPALI DÖNGÜ TERSİNE TEDARİK ZİNCİRİ AĞ TASARIMI

ÖZET

Sürdürülebilir kalkınma son yılların dikkat çeken konularından biri olmuştur. Bu kavram ilk kez dar anlamıyla Brundtland Komisyonu Raporu'nda ekonomik ve çevresel uyum olarak ortaya çıkmıştır. Tedarik zinciri sürdürülebilirliği, ürün veya hizmetin hayat ömrü boyunca çevresel, ekonomik ve sosyal etkilerinin iyi yönetişim uygulamalarının yönetimi olarak tanımlanmaktadır. Tedarik zinciri sürdürülebilirliğinin amacı pazara ürün ve hizmeti sunan paydaşların uzun dönemli çevresel, sosyal ve ekonomik değerlerini yaratmak, korumak ve geliştirmektir. Sürdürülebilir kalkınma, sürdürülebilir belediye, sürdürülebilir tarım, sürdürülebilir mimari, sürdürülebilir üretim vb. gibi birçok alanda önem kazanmıştır.

Üretim tesislerinin faaliyetleri sonucu oluşan katı atıklar, sulara karışan kimyasallar ve gazların negatif etkileri yıllarca göz ardı edilmiştir. 1990'ların sonlarında ulusal ve uluslararası platformlarda doğal kaynakları ve çevreyi koruma önemli bir hale gelmiştir. Teknolojik gelişmeler ve dünya nüfusunun artması üretim ve tüketim oranlarını katlayarak arttırmış ve bu da hammaddelere olan talebi arttırmıştır. Bu nedenle, kirlilik seviyesi artmış, kaynak kıtlığını arttırmış ve küresel ısınmaya sebep olmuştur. Bu pek çok şirketi ekonomik ve çevresel sürdürülebilirlik konusunda endişelendirmiş, birçok ülkenin çevresel konularda yasalar ve düzenlemeler geliştirmesine sebep olmuştur. Buna göre, tedarik zinciri yöneticileri ekonomik ve çevresel sürdürülebilirlik uygulamalarını belirlemek ve kullanmak durumundadır. Sürdürülebilir kalkınma birçok şirketin vizyonunda yer bulmuş ve şirketler için çevresel ve sosyal amaçlarla gelişebilmek için fayda sağlamıştır. Tedarik zinciri ve lojistik yönetimi de sürdürülebilir kalkınmadan etkilenmiş, dolayısıyla geleneksel problem çözme yaklaşımları yerini yeni sürdürülebilirlik temelli yaklaşımlara bırakmıştır.

Gelişmiş ülkelerdeki sanayiiler bu düzenlemelere uymak, çevre dostu stratejileri uygulamak ve karbon ayak izini azaltmak için tam teşekküllü üretim sistemleri kurmayı başarmışlardır. Bu sistemlerin hepsi geri kazanım etrafında toplanmaktadır. Geçmişte şirketler geri dönüşüm, yeniden kullanım vb. gibi geri kazanım sistemlerinin maliyetli olduğunu düşünmekteydiler. Çevresel konulara duyarlılık ve üretim maliyetleri arasında dengeyi sağlamak zor iken, bugün, geri kazanım sistemleri birçok şirket tarafından ekonomik bir kazanç olarak düşünülmektedir. Günümüzde müşterilerin çevre dostu ürünlere değer vermesi ve tercih etmeleri sebebiyle fiyatlandırma tek başına bir rekabet stratejisi olmaktan çıkmıştır. Bir başka deyişle, üreticiler müşteri talebi, yasal düzenlemeler ve ekonomik getiri açısından geri kazanım seçeneklerine yönelmektedirler.

Bu çalışmanın amacı atık yönetimi konusunda en önemli sektörlerden biri olan elektrik ve elektronik ekipmanı atıklarını minimize etmek için sürdürülebilir bir kapalı döngü tedarik zinciri ağ tasarımı ortaya koymaktır. Çalışma çok dönem, çok ürün ve çok amaç fonksiyon kapsamındadır. Literatürde kapalı döngü tedarik zinciri ağ tasarımı ile

ilgili birçok çalışma olmasına rağmen sürdürülebilirliğin ekonomik, çevresel ve sosyal boyutlarının üçünü de aynı anda ele alan çalışmaların sayısı azdır. Ayrıca, her geçen gün araştırmacılar sürdürülebilirlikle ilgili sayısal modelleri içeren çalışmalara yönelmektedirler. Bu nedenle, bu çalışmanın katkısı sürdürülebilirliğin üç boyutunu da göz önüne alan, çok ürünlü, çok amaçlı sayısal bir çalışma olan kapalı döngü tedarik zinciri ağı tasarlamaktır. Diğer yandan, çalışma içeriğindeki model sayesinde hem ilk defa kendi tersine lojistik ağını kurmayı hem de var olan ağ tasarımında iyileştirmeler yapmayı düşünen karar vericilerden oluşan farklı perspektifler tarafından kullanılmasına olanak sağlamaktadır.

Bu çalışma giriş, yazın taraması, dünyada ve Türkiye'de elektrik ve elektronik atık yönetimi analizi, matematiksel modeller ve uygulanması, sonuçlar ve tartışmalar ve öneriler olmak üzere altı bölümden oluşmaktadır. Literatür taramasında ilk olarak, tedarik zinciri yönetimi, sürdürülebilirlik kavramı, sürdürülebilirliğin ekonomik, çevresel ve sosyal boyutları, sürdürülebilir tedarik zinciri yönetimi tanımlanmıştır. Sonrasında, sürdürülebilirlik kavramı ile ilgili sayısal çalışmalardan örnekler verilmiştir. Ayrıca, sürdürülebilirlik ile ilgili literatürde yer alan farklı sektörlere ait çalışmalara yer verilmiş ve bu çalışmalar karşılaştırılmıştır. Literatür taraması bölümüne kapalı döngü tedarik zincirleri ve tersine lojistik tanımları da eklenmiştir. Kapalı döngü tedarik zinciri ve tersine lojistik kavramlarını içeren çok ürün, çok amaç, çok dönemli ağ tasarımı modelleri ile ilgili literatürde yer alan çalışmalar özetle açıklanmıştır.

Elektrik ve elektronik ekipmanları atık yönetimi analizi bölümünde,Türkiye atık yönetimi direktifi bilgileri Türkiye'yi atık yönetimi konusunda diğer ülkelerle karşılaştırmak için bilgileri verilmiştir. Türkiye'de atık yönetimiyle ilgili tarihsel süreçler, yönergelerin yayımlandığı ve yürürlüğe girdiği tarihler ve yönergelerin amaçları verilmiştir. Ayrıca, Çevre ve Şehircilik Bakanlığı'nın yıllara göre farklı kategorilerdeki elektrik ve elektronikli aletlerin kişi başı toplama hedefleri eklenmiştir. Bu bölümde son olarak, Çevre ve Şehircilik Bakanlığı'nın Avrupa Birliği Atık Yönetimi Direktifi'nden uyarladığı mevzuatta yer alan elektrik ve elektronikli eşyalar on kategoriye bölünmüştür.

Matematiksel model bölümünde ilk olarak parametreler, maliyetler ve karar değişkenleri tanımlanmıştır. Modele, üç amaç fonksiyonu eklenmiştir. İlk amaç fonksiyonunun amacı yeni toplama merkezleri ve yeni geri kazanım merkezlerinin ilk yatırım maliyetlerini, ürünlerin toplama ve geri kazanım maliyetlerini, tedarikçiden alınacak olan hammaddelerin maliyetlerini ve tesisler arasın gerçekleşen tüm taşıma maliyetlerini minimize etmektir. İkinci amaç fonksiyonunun amacı tesisler arası taşımadan kaynaklanan karbondioksit miktarının minimize edilmesidir. Son amaç fonksiyonunun amacı ise yeni toplama ve geri kazanım merkezlerin açılması sayesinde ortaya çıkacak iş gücü miktarından kaynaklanan sosyal faydanın maksimize edilmesidir. Daha sonra, modelin uygulamasında kullanılacak olan veriler Zimpl diliyle kodlanmış ve Scip Solver yardımıyla çözdürülmüştür.

Modellerin sonuçları sonuçlar ve tartışma bölümünde açıklanmıştır. Model dört tip ürün, üç tip taşıma aracı ile kapasiteleri bulunan toplamda otuz bir merkez ve tesisten oluşan örnek veri ile sekiz yıllık bir planlama ufku için uygulanmıştır. Bu 31 tesis ve merkezin; ikisi üretim tesisi, dördü dağıtım merkezi, yedisi müşteri noktası, biri var olan toplama merkezi, ikisi var olan geri kazanım tesisi, yedisi potansiyel toplama merkezi ve geriye kalan sekizi ise potansiyel geri kazanım tesisi olarak düşünülmüştür. Modelde üretim tesisi, dağıtıcı ve müşteri noktaları ekzojen kabul edilmiş, toplama merkezi ve geri kazanım tesisleri için karar verilmiştir. Ayrıca tüm tesisler ve merkezler arasında yıllar bazında gönderilen ürün tipi ve tedarikçiden alınacak olan hammadde türleri ve miktarları da belirlenmiştir.   son olarak gelecek çalışmalar için yararlı olabilecek öneriler sunulmuştur.

Modelin çok dönemli özelliğinin uygulanabilirliğinin kanıtı için de yıllara göre yüzde yirmi oranında artan talebe göre açılması gereken yeni toplama merkezleri ve geri kazanım tesislerinin belirlenmesi amacıyla duyarlılık analizi yapılmıştır.

Çalışmanın son bölümünde ise gelecek çalışmalar ve uygulama alanları için yararlı olabilecek bilgiler verilmiştir.

1. INTRODUCTION

Sustainable development is one of the most important issues of the last decade. For the first time, this concept has emerged in a narrow sense as economic and environmental compatibility in the Brundtland Commission Report. Supply chain sustainability is the management of environmental, social and economical impacts and the encouragement of good governance practices throughout the lifecycle of a good or service. The objective of supply chain sustainability is to create, protect and grow long-term environmental, social and economic value for all stakeholders involved in bringing products and services to a market (UN. Global Compact Supply Chain Report, 2008). The topic of sustainable development has gained importance in many different fields, such as sustainable municipality, sustainable agriculture, sustainable architecture, sustainable production etc. There are negative effects from many factors such as solid waste, chemicals mixed with water, gases which are produced by manufacturing facility activities which have been neglected for many years. By the end of the 1990s, protecting natural resources and the environment became a significant issue in both national and international arenas (Büyüközkan and Vardaroğlu, 2008). Both technological improvements and a growing world population have sped up the rate of production and consumption of products as well as increased the demand for raw materials as a result. For this reason, pollution levels increased, which led to resource scarcity and global warming. This made lots of enterprises and companies worry about environmental and economical sustainability, so much so that many countries developed new regulations about green issues. That's why supply chain managers should identify and use economic and environmental sustainability applications (Green et al, 2012). Sustainable development has taken place in many companies' visions and offers an important perspective that enables prediction of growth associated with the ecological and social goals for the company (Altuntaş and Türker, 2012). The supply chain and logistics management approach of companies is affected by the sustainable development concept and the traditional problem solving approach is about to give way to the new sustainability based approach.

Industries in developed countries set up full-fledged systems to follow these regulations, implementing environmentally friendly strategies to reduce their carbon footprint (Lei Xu et al, 2013). These systems are all about recovery options. In the past, companies thought that recovery options, such as recycling, to be a great cost. It was difficult to strike a balance between environmental issues and production costs. Today however, recovery options are considered to be an economic gain by a lot of companies. Moreover, pricing is no longer a unique competitive strategy since customers give today value and prefer environmentally friendly products. In other words, recovery options are considered by manufacturers due to customer demand, regulations and economical return.

1.1 The Aim of the Study

The aim of this study is to put forward a sustainable closed loop supply chain network design for minimize the waste of electric and electrical equipment which is the one of the most crucial sectors in terms of waste management. The study consists of multi-period, multi-product reverse logistics concept. There are lots of studies in the literature about closed loop supply chain network design, but there is few studies which take into account all of three dimensions of sustainability (economic, environmental and social dimensions). Also, there is still less studies about sustainability with quantitative model in the literature. Therefore, the contribution of this study is to fill the gap about the mathematical closed loop reverse supply chain network design model in multi-product, multi-objective and multi-period aspects for all of three dimensions of sustainability for decision making.

1.2 The Scope of the Study

This study includes six parts; introduction, literature review, analysis of WEEE management in Turkey and other countries, mathematical model and its application with an illustrative example, results and conclusion and recommendation. In the literature review, supply chain management, the concept of sustainability, dimensions of sustainability and sustainable supply chain management will be defined firstly. After that, it will continue with the quantitative studies about sustainability concept. In addition, sustainability will be examined and compared with different sectors. The definitions of closed loop supply chain and reverse logistics will be included. Then, studies which are examples of closed loop supply chain and reverse logistics network design models with multi-product and/or multi-period and/or multi echelon concepts will be explained.

In the analyses of the WEEE management, EU waste management directive and Turkey waste management directive information will be given to compare and contrast Turkey with the other countries in terms of WEEE management. Moreover, the targets for collection and recovery based on years will be investigated in this part.

In the mathematical model part, the parameters, costs and decision variables will be defined first. The mathematical model is both for one-time decision making and multi-period decision making. Then, three objective functions will be added. The aim of the first objective function will be to minimize first costs of new collection centers and new recovery centers, costs of collection and recovery the products, the cost of acquisition of raw material from the suppliers and total transportation costs among nodes. The aim of second objective function is to minimize CO_2 of the transportation activities between all nodes. Maximizing the increase of social benefits through opening new collection and recovery centers is the purpose of the last objective function. After that, data will be shown for the application of the model.

The results of the illustrative data and its comment will be analyzed in the results and discussion part.

At the end, conclusion and recommendation part will contain some critical points to give beneficial information for further studies.

2. LITERATURE REVIEW

2.1 Sustainability and Sustainable Supply Chain Management

The supply chain encompasses all activities associated with the flow and transformation of goods from raw material stage (extraction), through to the end user, as well as the up and down the supply chain (Handfiled and Nichols, 1999).

Supply chain management (SCM) is the integration of these activities through improved supply chain relationships to obtain a sustainable competitive advantage (Handfiled and Nichols, 1999).

Traditionally, SCM has been described as the management of physical,logical and financial flows in networks of intra-and inter-organizational relationships together adding value and achieving customer satisfaction(Stock and Boyer, 2009).

From a process-oriented or cross-functional point of view, SCM comprises planning, sourcing, production and distribution logistics (Supply-Chain Council, 2008), but is not exclusively consantrated on one of these areas (Cooper, et al, 1997).

Sustainable development is defined as “ a development that meets the needs of the present without comprimising the ability of future generations to meet their own needs” (WCED, 1987).

While various understandings of sustainability exist, one central concept helping to operationalize sustainability is the triple bottom line approach, where a minimum performance is to be attained in the enviromental, economic and social dimensions (Elkington, 2002).

Dyllick and Hockerts (2002) have framed the three dimensions of sustainability as the business case (economic), the natural case (environmental) and the societal case(social). The dimensions of sustainability is shown in Figure 2.1.

On account of growing concern about sustainability of local or global environment, community, society or economy, sufficient design of product life cycle become progressively important as well as design of a product itself. Therefore the business model eligable to designed product life cycle should also be designed concurrently. It is expected to initiate environmental, social and sometimes ethical aspects to traditional business framework. In order to take them into account, it is very critical to

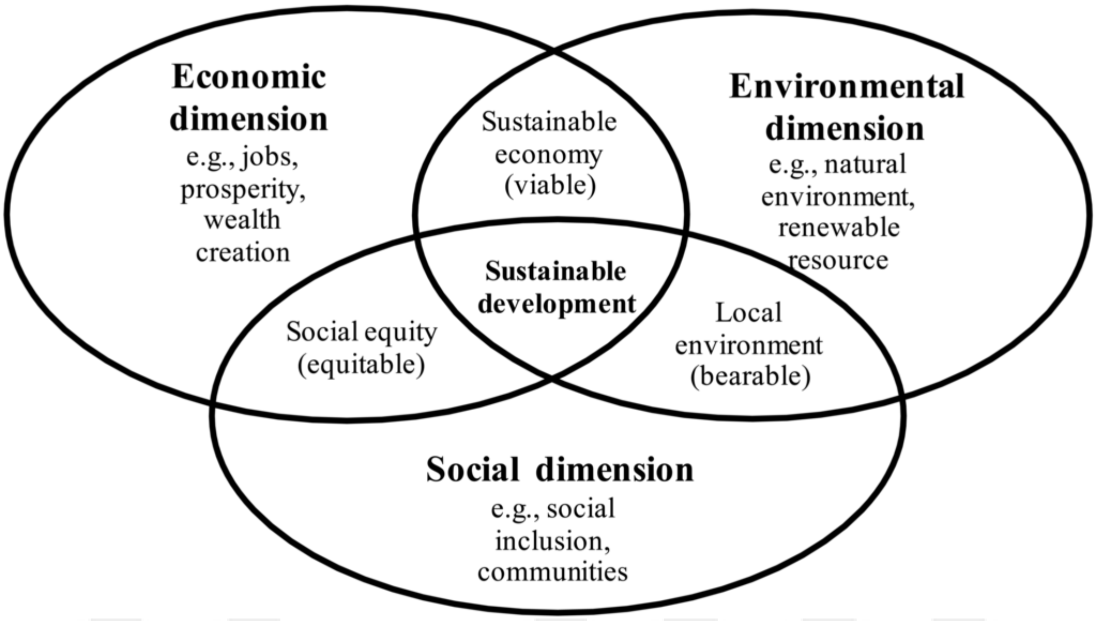

Figure 2.1 : Dimensions of sustainability (Url-3).

widen business extent to consider indirect cause effect chains outside of the company that do not directly have an impact on its profit (Kondoh et al, 2014).

Sustainable business is defined by its aspects to balance triple bottom lines (i.e., profit, planet, and people). In sustainable business design, it is decisive to contemplate interaction between the core business and external environment, which does not seem to effect the profit of the core business but is required to clarify their deliberate environmental and social value statement (Kondoh et al, 2014).

Sustainability, the consideration of environmental factors and social aspects, in supply chain management (SCM) has become a significant topic for researchers and practitioners. The application of operations research methods and related models, i.e. formal modeling for closed-loop SCM and reverse logistics has been thoroughly examined in formerly published research (Brandenburg et al, 2014).

Combining environmental and social perspectives with financial aspects, known as the triple-bottom-line (TBL) dimensions of organizational sustainability, has continually gained relevance generally for managerial decision making and specifically for supply chain management (SCM) and operations management (Carter and Rogers, 2008).

Bozbura et al. (2011), states that companies, which are knowledgeable of the fact that doing business with regard as worthy of special consideration to sustainability, gain competitive benefits over the other companies in the market since environmental sustainability has many different facets to one and other, managers in the supply chain endeavor where to begin to diversify their way of doing business (Bozbura et al, 2011).

Sustainability requirements of, for instance, a steel supply chain could be completely different than the supply chain for children's toys or fast fashion clothing. Consequently, a sectorial snapshot is needed for the proposition of farther applications in major supply chains or for expansive sector specific implementations to vying supply chains (Turker and Altuntas, 2014).

Alexandre (2011) determines that the seven most critical environmental requirements and economic aspects for sustainable practice are as follows: reduction in waste and emissions, reduction in energy intensity of goods and services, use of renewable and sustainable energuy resources, maximum use and re-use of recycled components and materials, measurement and assessment of business impact on ecosystems, standard measures for evaluating sustainability performance, and environmental consciousness pervading the culture of an organization.

Sustainable supply chain management (SSCM) is defined as the management of material, information and capital flows as well as cooperation among companies along the supply chain while taking goals from all three dimensions of sustainable development, i.e., economic, environmental and social, into account which are derived from customer and stakeholder requirements. In sustainable supply chains, environmental and social criteria need to be fullfilled by the members to remain within the supply chain, while it is expercted that competiveness would be maintained through meeting customer needs and related economic criteria. This definition is rather broad and joins together those given for sustainability and supply chain management. It is also able to integrate green/environmental supply chain management as one part of the wider field (Seuring and Müller, 2008).

There are several forces of historical tribute that conduce to sustainability concern. First of all, there are significant number of long term challenges including climate change, population ageing, desertification, water scarcity, pollution and critical raw material scarcities that the world is facing (Montalvo et al, 2006). Secondly, the world is in a new multi-polar period that the rules of the competitive game has totally changed due to the global economic context. The policies that have traditionally ruled global competitiveness are changing very fast. Leading economies and newcomers into international markets have become proficient in not only the know-how for cost-driven competition Contractor et al. (2010), but they have also become innovative and sustainable in traditional and in specific high-tech sectors (Montobbio et al, 2010). Last of all, in many advanced economies, governments can no longer depend on electorate's confidence and legimacy in policy agendas to ensure societal welfare and employment following the 2007-08 economic crisis. The financial depression that started in 2008 has made it definitely clear how short term-profitability business approaches and related master plans, policies and actions of individual companies can cause global economic, ecological and ethical breakdowns (Boons et al, 2012). These incidents have given rise to the perception that most of the companies operate on business models that are not sustainable.

Contrary to traditional SCM, which typically concentrates on economic and financial business performance, sustainable supply chain management is characterized by explicit integration of environmental or social objectives which extent to economic dimension to the TBL (Seuring and Müller, 2008). In this context, SSCM focuses on the forward SC and closed loop supply chain management (CLSCM) embracing reverse logistics, remanufacturing and product recovery (Brandenburg et al, 2013).

The rising prominence of this area, academically, socially and economically is reviewed on the geometric growth of related scientific publications during the past two decades and specifically in past decade (Min and Kim, 2012).

For CLSCM, quantitative models are frequently applied and practical (Flleishmann et al, 1997). In contrast to this circumstance, the majority of models employed for SSCM are more conceptual. Recently, the quantity of formal modeling efforts are improving (Brandenburg et al, 2013).

It is visible from the literature that reverse-oriented CLSCM models are widely accepted but a significant number of forward SCM models also exist about sustainability (Min and Kim, 2012).

To help further catalyze research in this field, which has several opportunities to enhance organizational, industrial and commercial sustainability, further comprehension of the common and unique modeling characteristics is required. Some SSCM reviews are present now but most of it is descriptive (Brandenburg et al, 2013).

The earliest related literature reviews indicate green product and process development, green operations management, remanufacturing and CLSCM as fields to combine planet and people related matters into SCM, but these approaches are lack of social aspects of SSCM (Brandenburg et al, 2013).

A sectoral focus of scientific SSCM research is of particular interest, which is not yet covered in model based SSCM research. Despite automotive, chemical and electronics industries have fewer analysis, emprical researches concentrate on transportation, textile and consumer product fields (Carter and Easton, 2011).

To lead the policy makers and researchers about which sectors need further academic and policy comprehensive modeling study, identifying a sectoral preference or lack can be helpful (Brandenburg et al, 2013).

SSCM is defined as “the strategic, transparent integration and achievement of an organization’s environmental, social and economic goals in the systematic coordination of key inter-organizational business processes for improving the long-term economic performance of the individual company and its chains” (Carter and Rogers, 2008). Besides, SSCM is mainly intended to improve business and environmental performance in a supply chain network (Lin and Tseng, 2014).

Sustainability leads firms not only to establish competitive priorities but also to evolve sustainable development, as a consequence of this SSCM suggests that proactive sustainability yields competitiveness, economic benefits and better corporate social responsibility (Lin and Tseng, 2014).

Since the supply chains are becoming increasingly more important in sustainable development, most companies pay special attention to SSCM. The main objective of SSCM is to ensure good manufacturing conditions throughout the value chain to diminish the environmental, labor and social impacts of business operations (Turker and Altuntas, 2014).

SSCM can be defined as the integration of social, economic and environmental practices within an international supply chain that provides green products, excellent services and accurate information, sharing those benefits with all employes, shareholders, business partners and the wider community (Kuik et al, 2010).

Enablers of implemantation of SSCM are determined as “employment stability, health and safety issues, community economic welfare, adoption of safety standards, adoption of green purchasing, adoption of green practices, eco-design, government regulations, hazard management, customer satisfaction, environmental cost, economic input to infrastructural development, improvement of product characteristics” (Diabat et al, 2014).

Bauman and Genoulaz (2014) create a framework for sustainable performance assesment of supply chain management. Economic fields of SSCM covers five fields: reliability, responsiveness, flexibility, finance and quality. They present reliability in particular through four sub-fields; customer service, suppliers’ service, reliability of stocks and reliability of forecasts. Responsiveness is analyzed in particular eight sub-fields; supply chain responsiveness, design responsiveness, purchase responsiveness, source responsiveness, production responsiveness, delivery responsiveness, sell responsiveness, return responsiveness. Financial performance is evaluated in seven sub-fields; which are design cost, purchase cost, source cost, production cost, delivery cost, return cost and supply chain cost. To evaluate flexibility, they have borrowed four sub-fields; suppliers flexibility, supply flexibility, production flexibility and delivery flexibility. They define the impacts of quality in-three sub-fields; product&service quality, quality performance of suppliers and production quality. Environmental fields of SSCM is defined with five fields: environmental management, use of resources, pollution, dangerousness and natural environment. Environmental managements' sub-fields are environmental budget, environmental certification, environmental compliance and workers implications in environmental protection. They define five sub-fields linked to use of resources as renewable energy, recycled water, inputs stemming from the recycling, recyclable outputs and recyclable wastes. Pollution is divided to four sub-fields; water pollution, air pollution, land pollution and other pollution. Dangerous inputs, dangerous outputs and dangerous wastes are the subfields of dangerousness. They propose to divide natural environment field into four sub-fields; eco-systemic services, land use, respect of biodiversity, development of urban and rural areas. Social dimension of SSCM has five sub-fields: work conditions, human rights, societal commitment, customers issues and business practices. Work conditions is a term which includes employment, work conditions, respect of social dialog, health and security and human resources development sub-fields. Child and forced labor, freedom of association and discrimination are three subfields of human rights field. Societal commitment field can be presented in five sub-fields; involment in local community, education, culture and technological development, job creation, healthcare, societal investment. They evaluate customer issues in four sub-fields; marketing and information, healthcare and security, sustainability-related supply chain risks in the endogenous and exogenous framework. Endogenous environmental risks are environmental accidents (e.g. fires, explosions), pollution (air, water, soil), non-compliance with sustainability laws, emission of greenhouse gases, ozone depletion, energy consumption (unproductive use of energy), exessive or unnecessary packaging and product waste. Endogenous environmental risks are natural disasters (e.g. hurricanes, eartquakes, floods), water scarcity, heatwaves and droughts. Endogenous social risks are excessive working time, work-life imbalance, unfair wages, child labour/forced labour, discrimination (race, sex, religion, disability, age, political views), healthy and safe working environment, protection of private life and access to essantial services. The last social field, business practices, is divided to three sub-fields; fight against corruption, promotion of corporate social responsibility in the sphere of influence, fair-trading.

Giannakis and Papadopoulos (2016) identify exploitative hiring policies (lack of contract, insurance) and unethical treatment of animals. Exogenous social risks are pandemic, social instability, demographic challenges and ageing population. Endogenous financial/economic risks are bribery, false claims, dishonesty, price fixing accusations, antitrust claims and tax evasion. Exogenous financial/economic risks are boycotts, litigations, energy prices votality and financial crises.

Chaabane et al. (2011), propose a bi-objective mathematical model as an example of Sustainable Supply Chain Network Design (S-SCND). The objective of economic sustainability is to minimize the total logistics cost of the supply chain, while the objective of environmental sustainability is to minimize total emission quantity of green-house gas (GHG). This article shows that S-SCND provides long-term competitive advantage through alinment of economic, social and environmental goals.

The study of Diabat (2014) identifies influential enablers for SSCM by using Interprative Structural Modelling from thirteen enablers. They designate five enablers include adoption of safety standards, adoption of green practices, community economic welfare, health and safety issues, and employment stability for Indian textile sector. The study shows, safety perspective enablers provide additional motivation when compared to the other enablers for SSCM adoption.

Turker and Altuntas (2014) reveal a SSCM framework for fast fashion industry in developing countries based on the framework of Seuring and Müller (2008). They examine nine fast fashion companies (Calida, Mango, C&A, H&M, Inditex, Marimekko, Oberalp, Puma and Switcher) that use same reporting guidelines. According to their study, these companies significantly focus on supplier compliance with their code of conduct, employing further auditing and monitoring activities to prevent production problems, set of sustainability criteria for their suppliers and improve overall supply chain performance.

Lin and Tseng (2014) investigate the hierarchical structure and linguistic preferences to identify the competitive priorities under SSCM in electronic focal manufacturing firms in Taiwan. They identify four SSCM aspects which are supplier, customer, internal sustainable business process, growing and learning performance. Criterias of supplier aspect are price of parts, high delivery reliability, high delivery speed, low costs (transport, administration, R&D collaborations), quality of parts and supplier ability to quality problems. Criterias for customer aspect are level of customer percieved value of product, range of products and services, flexibility of service systems to meet particular customer needs, responsiveness to urgent deliveries, information carrying cost, quality of delivered goods and achievement of defect free deliveries. Criterias for internal sustainable business process are selected as effectiveness of master production schedule (MPS), capacity utilization, efficiency of purchase order cycle time, frequency of delivery, lead-time reduction, setup time reduction, ability to change priorities of jobs on the shop floor, increase capacity utilization, ability to change machine assignments of jobs on the shop floor, operating capacity, competitive costs, procurement of raw materials, innovation in internal process controls on competitive priorities and reducing the product costs.Employee awareness, order entry methods, product development cycle time and accuracy of forecasting techniques are the criterias of growing and learning performance aspect. The competitive priorities are cost, quality, dependability, flexibility and innovation. The results of the study shows the importance of each of the criterias with respect to competitive priorities.

Bozbura et al. (2011), offers a proposed model for SSCM. Their model includes ten indicators, which are the waste disposal, the cost of energy, staff training, implementing control technologies, buying environmental friendly material, support of senior management, stakeholders relationship, amount of green manufacturing, recycle and remanufacturing rate, and disassembly and disposal rate. As a result, green manufacturing has the highest value among the other indicators.

2.2 Closed Loop Supply Chain Network Design and Reverse Logistics

Sustainable development and reverse logistics has drawn the quite attention of many scholars recently (Lee and Lam, 2012). Because, closed loop supply chain is an environmentally and economically sound way to achieve many of the goals of sustainable development (Winkler, 2011).

In an environmentally responsible logistics approach, the intension of minimizing overall effect is intended to traditional logistics system (Logozar et al, 2006). Reverse logistics and CLSC are latterly more visible as vital logistical structures for many discrete-part manufacturers whose products amenable to remanufacturing/refurbishing practices. Characteristic models include automotive and electronics products commonly posses relatively high recoverable value and long product life cycles (Easwarn et al, 2010).

Firms such as HP, Kodak, Xerox and Dell adopted the practice of product recovery since it has a potential to increase cost-effectiveness and environmental benefits created by the reuse of resources by that means saving on raw material requirements (Easwarn et al, 2010). Thus, national and local authority should support the reverse logistics practices to facilitate the acquisition of production inputs and raw materials, and to decrease the damage to environment during the product life cycle (Rodriguez et al, 2013).

Literature reviews shows, the statements of reverse logistics, reverse distribution, retro logistics and return logistics has roughly the same content. The definition of reverse logistics by Stock and Kopicky (1999) corresponds to a broad statement including disposal of toxic and non-toxic waste of the production and logistics management. Accordingly, Stock and Kopicky focus on the reduction of waste and they put the reverse logistics into the concept of environmental management. Pohlen and Farris (1992) defines reverse logistics as the movement of goods from the customers to manufacturer in a distribution channel. On the other hand, Pohlen and Farris focus on the position and direction of the sender and receiver in the supply chain. Reverse logistics is defined as "cost effective planning, implementation and controlling process of the flow of raw materials, work-in-process inventories, final goods and their related information from the consuming point origin point with the purpose of value creation, recapturing and appropriate disposal" (Rogers and Limke, 1999). The movement of goods from the final destination to initial point for regaining value creation and dispose in an appropriate manner (Logozar et al, 2006).

By using reverse logistics, used materials are converted to new products and materials that have the market value by reusing, remanufacturing, refurbishment and recycling. Therefore, typical supply chain becomes a closed loop under favor of reverse logistics (Hervani et al, 2005). Because of this reason, closed loop supply chain management consists of both forward and reverse flow. Forward supply chains start with the raw material that ends up at the customer, while reverse supply chains define the collection of the end of life products from customers that is recovered, recycled or reused accordingly depends on the quality and if they do not reach to the required quality level, they will be disposed (Guide and Harrison, 2003).

Despite the fact that reverse logistics is similar to forward logistics in terms of the activities such as inventory management, delivery scheduling and storage; it is different from the forward logistics with the forecasting method, distribution structure, quality and value of the product etc. The differences between forward and reverse logistics are summarized at the following table below (Table 2.1).

Table 2.1: Differences between forward and reverse logistics (Rogers and Lembke, 1999).

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

(Lembke and Rogers,2002) Figure 2.2 shows the basic flow diagram of RL activities where the complexity of operations and the value recovered increase from bottom left to top right.

Jindal et al. (2015), propose a network design for a multi-product, multi-time, multi echelon closed loop supply chain framework in an uncertain environment. The proposed CLSC network is represented by a fuzzy mixed integer linear programming

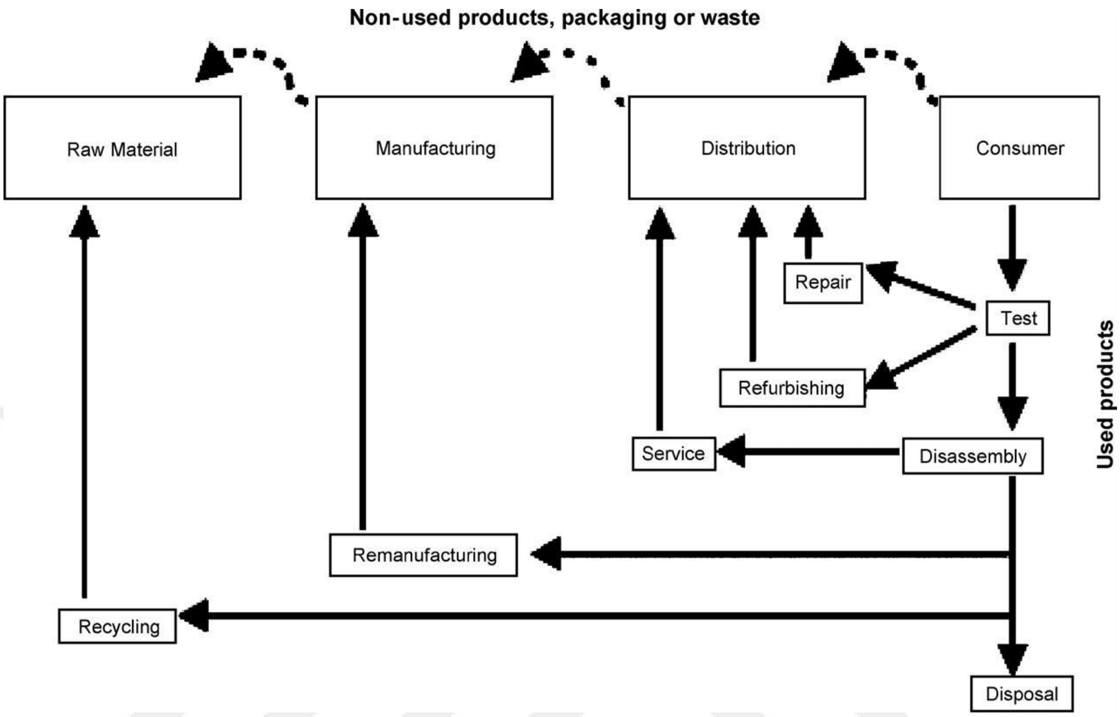

Figure 2.2 : Basic flow diagram of RL activities.

(MILP) model to decide optimal location and allocation of parts at the facility, inventory level of the parts, number of products to be remanufactured and number of parts to be purchased from external suppliers in order to maximize the profit of organization.

Easwaran and Üster (2010) consider a multi-product closed-loop logistics network design problem with hybrid manufacturing/remanufacturing facilities and finite capacity hybrid distribution/collection centers to serve a set of retail locations. In their model, hybrid production plants, hybrid collection centers, hybrid distribution centers and hybrid remanufacturing centers are opposed to separate plants. They determine the locations of facilities in both forward and reverse channel networks and incorporate processing and storage capacity restrictions.

Das et al. (2015) integrate environmental concerns in a closed loop supply chain model to improve overall SC performance in terms of sustainability and business operational metrics. Their model includes modular product design for facilitating faster manufacturing, disassembly, remanufacturing, refurbishing, and repairing, using new, reusable and repairable components, and modular subassemblies. The model plans sustainable module formation, production process for components and products, and transportation and distribution routes to obtain optimum business performances and address environmental concerns for harmful emissions and energy spent. The research proposes to collect end-of-life and other customer returned products through retailers by motivating both retailers and customers with an incentive scheme. Numerical example in their study illustrates the applicability of their approach and model.

Qiang et al. (2014) propose a two-period CLSC network model with manufacturers that compete with one another to serve the consumers of various demand markets. Manufacturers decide on production quantity and remanufacturability level in the first period. They assume that those manufacturers who are proactive in the product remanufacturability design incur a higher production cost for new product but will reap the benefit by having a lower production cost for the remanufactured product in the second period. The consumers are assumed to be conscious about the price and quality of the product and therefore, discount their willingness to pay for the remanufactured product. In spite of being proactive in product remanufacturability design decreases the market share of the new product for the competitors who are reactive in choosing the design, the former product is more profitable due to the capture of additional market share of the refurbished product. Also, they find that if all customers have a higher willingness to pay for refurbished product, being proactive is less promising.

Garg et al. (2015) investigate a multi-criteria optimization approach to manage environmental issues in CLSC-ND. They formulate a bi-objective non-linear programming problem, and in order to solve it they propose an interactive Multi-Objective Programming Approach Algorithm. Their model determines the optimal flow of parts and products in the CLSC network and the optimum number of trucks hired by facilities in the forward chain of network. They have a numerical experimentation of the proposed model to validate the applicability of the model with the help of the data from a real life case study. The case presented in the paper is based on a geyser manufacturer, and its application on the model provides them with the underlying tradeoffs between the two objectives. The model also results with a very interesting fact that with the implication of the extended supply chain, a firm can create a green image of their product which eventually results in an increase on their demand while significantly reducing their usage of transportation in both directions.

Chaabane et al. (2010) propose a comprehensive methodology to address sustainable supply chain design problems where carbon emissions and total logistics costs, including suppliers and sub-contractors selection, technology acquisition and the choice of transportation modes, are considered in the design phase. The proposed methodology provides decision makers with a multi-objective mixed integer linear programming model to determine the trade-off between economic and environmental considerations. The model is illustrated through the study of a Canadian company operating in the steel industry which is facing a new legislation that caps carbon emissions. The results show how emission trading market can be used to reduce the carbon dioxide abatement cost.

Pishavee et al. (2010) propose a robust optimization approach to closed-loop supply chain network design under uncertainty. Firstly, they develop a deterministic, mixed-integer linear programming model for designing a closed-loop supply chain network. Secondly, the robust counterpart of the proposed mixed-integer linear programming model is presented by using recent extensions in robust optimization theory. Finally, they are compared to those generated by the deterministic mixed-integer linear programming model in a number of realizations under different test problems to assess the robustness of the solutions obtained by the novel optimization theory.

Wenzhi et al. (2006) review the implementation of strategies of WEEE treatment and the recovery technologies of WEEE. It presents the current status of WEEE and corresponding responses adopted so far in China. The concept and implementation of scientific development is critical to the sector of electronics as one of the important industrial sectors in China's economy. To achieve this objective, it is significant to recycle WEEE sufficiently to comply with the regulations regarding WEEE management, and to implement green design and cleaner production concepts within the electronics industry with the upcoming EU and China legislation in a proactive manner.

Yang et al. (2007) also study WEEE flow and mitigating measures in China. They identify the sources and generation of WEEE in China and calculate WEEE volumes. The results show that recycling capacity must increase if the rising quantity of domestic WEEE is to be handled properly. Simultaneously, suitable WEEE treatment will generate large volumes of secondary resources. They describe the existing WEEE flow at the national level and future challenges and strategies for WEEE management in China.

Walther and Spenger (2005) analyze the impact of WEEE directive on reverse logistics in Germany. They think that essential changes in the field of treatment of electronic products in Germany are expected due to the new regal requirements owned. On the other hand, the consequences in terms of changes of organization and material flows of the German treatment system are currently unknown. Their contribution is to predict relevant changes in this context. That sets the framework for a deduction of recommendations for political decision makers and actors of the treatment system.

3. ANALYSIS OF WEEE MANAGEMENT IN TURKEY

The first study about waste of electric and electrical equipment in Turkey is made by Ministry of Environment and Urban Planning with a regulation for the limitation of some certain hazardous substances in 2009.Regulation was published in the Official Gazette in 30.05.2009 and entered into force in 2009. The purpose of this regulation was to establish the guidelines for the restriction of use of certain hazardous substances in electric and electronical goods, determination of the application to be exempted from this limitation and recovering or disposal of waste of electric and electronical equipments in order to protect environment and human health (Ministry of Environment and Urban Planning, 2008).

Waste of Electric and Electrical Contolling Regulations was enacted by Ministry of Environment and Urban Planning with the post in the Official Gazette in 22.05.2012 (Ministry of Environment and Urban Planning, 2012). The purpose of the regulations was the same with the regulations which was published in 2009. The companies which had letter of conformity collected 4000 tons of WEEE in 2009, while they collected only 1818 tons of WEEE in 2006. The household WEEE collection targets are shown in the table below (Table 3.1).

Table 3.1: The household WEEE collection targets.

		Waste Collection Target by Year (kg/capita-year)				
	EEE Categories	2013	2014	2015	2016	2018
1.	Refrigerators/Cooling/Air-conditioning appliances	0.05	0.09	0.17	0.34	0.68
2.	Large white appliances (with the exception of refrigerators/cooling/air-conditioning appliances)	0,1	0,15	0,32	0,64	1,3
3.	Televisions and monitors	0,06	0,10	0,22	0,44	0,86
4.	IT and telecommunication & consumer equipment(with the exception of televisions and monitors)	0,05	0,08	0,16	0,32	0,64
5.	Lighting equipment	0,01	0,02	0,02	0,04	0,08
6.	Small household appliances, electrical and electronic tools, toys, sports and leisure equipment, monitoring and control tools	0,03	0,06	0,11	0,22	0,44
	Total Houshold WEEE (kg/capita-year)	0,3	0,5	1	2	4

Table 3.2 shows recyling targets and Table 3.3 shows recovery targets according to types of equipments' categories (Table 3.2 and Table 3.3).

Table 3.2 : Recycling targets.

Electrical and Electronic Equipment Categories	Year 2013	Year 2018 (%) by weight
Large household appliances (%)	65	75
Small household appliances (%)	40	50
IT and telecommunications equipment (%)	50	65
Consumer equipment (%)	50	65
Lighting devices and equipment (%)	20	50
Gas discharge lamps	55	80
Electrical and electronic tools (%)	40	50
Toys, leisure and sports tools (%)	40	50
Medical devices (%)	--	--
Monitoring and control devices and tools (%)	40	50
Automatic dispensers (%)	65	75

Table 3.3: Recovery targets.

Electrical and Electronic Equipment Categories	Year 2013	Year 2018 (%) by weight
Large household appliances (%)	75	80
Small household appliances (%)	55	70
IT and telecommunications equipment (%)	60	75
Consumer equipment (%)	60	75
Lighting devices and equipment (%)	50	70
Gas discharge lamps	70	80
Electrical and electronic tools (%)	50	70
Toys, leisure and sports tools (%)	50	70
Medical devices (%)	--	--
Monitoring and control devices and tools (%)	50	70
Automatic dispensers (%)	70	80

The electric and electronic equipment categories is shown in the below:

1. Large household appliances
2. Small household appliances
3. IT and telecommunications equipment

4. Consumer equipment
5. Lighting equipment
6. Electrical and electronic tools (with the exception of large-scale stationary industrial tools)
7. Toys, leisure and sports equipment
8. Medical devices
9. Monitoring and control instruments
10. Automatic dispensers

4. MATHEMATICAL MODEL

Sets:

P	: Set of product types
Q	: Set of raw material types
T	: Set of time periods (years)
M	: Set of manufacturing facilities
D	: Set of existing distribution facilities
C	: Set of existing and potential collection centers
R	: Set of existing and potential recovery facilities
B	: Set of customer locations (Buyers)
K	: Set of transportation modes
L	: Set of all locations
U	:Set of all nodes

Parameters:

D_{jpt}	: demand of product $p \in P$ of the customer $j \in B$ in time $t \in T$
A_{qp}	: required amount of product $p \in P$ to produce one unit of product $q \in Q$
G_{jpt}	: end of life products $p \in P$ generated at customer point $j \in B$ in time $t \in T$
F_{qp}	: generated amount of product $p \in P$ from one unit of product $q \in Q$
V_p	: volume of product $p \in P$
Cap_j	: capacities of facilities of node $j \in U$
$CCap_j$	: campaign capacity of node $j \in D$
Cap_k	: capacity of transportation mode $k \in K$

CO_{2k} : generated amount of CO_2 per km during transportation by using transportation mode $k \in K$

β : required percentage recover from collected parts at pottential and existing recovery centers

α : conservation of mass ratio

dis_{ij} :distance between node $i \in U$ and node $j \in U$, i≠j

S_j : increase in social utility when node $j \in C \; or \; R$ is decided to open

Costs:

FC_j : fixed cost of opening a new collection center or new recovery center $j \in C \; or \; j \in R$

E_{pj} : unit recovery cost of product $p \in P$ in an existing or potential recovery center $j \in C \; or \; j \in R$

TC_{pk} : unit transportation cost per km of product $p \in P$ by using transportation mode $k \in K$

PC_{qm} : unit purchasing cost of raw material $q \in Q$ for manufacturing facility $m \in M$

Decision Variables:

y_{jt} $\begin{cases} 1, \text{ if collection center or recovery center } j \in C \text{ or } j \in R \text{ is decided to open in time } t \in T \\ 0, \text{otherwise} \end{cases}$

w_{ijkt} $\begin{cases} 1, \text{ if transportation mode } k \in K \text{ is decided to serve between node i and j} \in U \text{ in time } t \in T \\ 0, \text{otherwise} \end{cases}$

z_{ipt} : $amount \; of$ product $p \in P$ manufactured in facility $i \in M$ in time $t \in T$

H_{iqt} : amount of raw material $q \in Q$ purchased from suppliers for manufacturing facility $i \in M$ $t \in T$

x_{ijkt} : amount of product $p \in P$ or raw material $q \in Q$ which moves from node i to node $j \in U$ with transportation mode $k \in K$ in time $t \in T$

A multi-objective mathematical model is shown with the equations 4.1 to 4.16 according to the defined parameters and decision variables and the flow of products and raw materials is shown at the figure below (Figure 4.1).

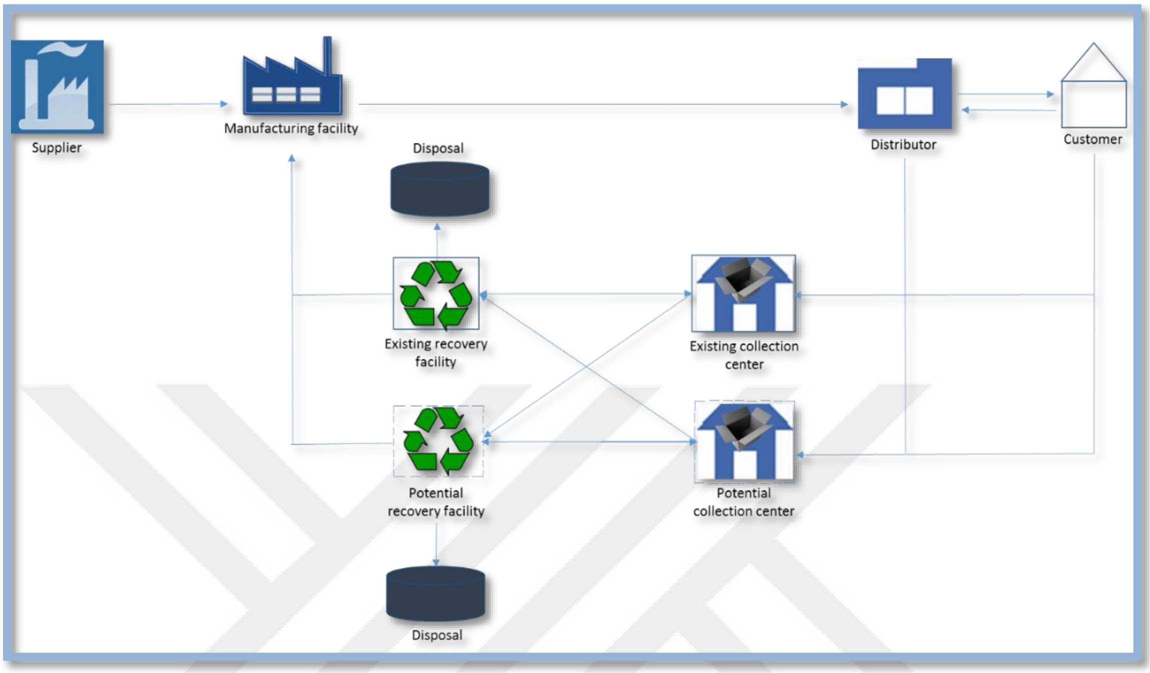

Figure 4.1 : Forward and reverse flow of the products and raw materials.

$$\boldsymbol{Min} \quad \left\{ \sum_{j\in R\cup C} FC_j y_{jt} + \sum_{q\in Q}\sum_{t\in T}\sum_{J\in M} PC_{qj} H_{qjt} + \sum_{t\in T}\sum_{i\in U}\sum_{j\in U}\sum_{k\in K}\sum_{p\in P} TC_{pk}\, x_{ijpkt} dis_{ij} SS_{ij} + \sum_{t\in T}\sum_{k\in K}\sum_{p\in P}\sum_{i\in C}\sum_{j\in R} E_{pj}\, x_{ijpkt} \right\} \tag{4.1}$$

$$\boldsymbol{Min} \quad \left\{ \sum_{t\in T}\sum_{i\in U}\sum_{j\in U}\sum_{k\in K} SS_{ijk}\, dis_{ij}\, w_{ijkt} CO_{2k} \right\} \tag{4.2}$$

$$\boldsymbol{Max} \quad \left\{ \sum_{j\in R\cup C} S_j\, y_{jt} \right\} \tag{4.3}$$

$$\sum_{p\in P} 0.0192 x_{ijpkt}\, V_p SS_{ij} \leq Cap_k w_{ijkt} \tag{4.4}$$

$$\sum_{k\in K}\sum_{p\in P}\sum_{i\in U-B} x_{ijpkt} V_p \leq Cap_j y_{jt} \tag{4.5}$$

$$\sum_{i\in D} x_{ijpt} \geq D_{jpt} \tag{4.6}$$

$$y_{jt} = 1 \tag{4.7}$$

$$\sum_{p\in P}\sum_{k\in K}\sum_{b\in B} x_{ijpk} V_p \leq CCap_j \tag{4.8}$$

$$\textstyle\sum_{i\in U} \alpha_{ip} x_{ijp} = \sum_{m\in U} x_{jmp} \quad \forall\, j \in U, i \neq j, j \neq m \tag{4.9}$$

$$\textstyle\sum_{i\in C}\sum_{p\in P}\sum_{k\in K}\sum_{j\in R} x_{ijpkt} \geq \beta \sum_{j\in C\cup D}\sum_{i\in B}\sum_{p\in B}\sum_{k\in K} x_{ijpkt} \quad \forall\, t \in T \tag{4.10}$$

$$\textstyle\sum_{i\in U}\sum_{k\in K} \alpha\, x_{impkt} = \sum_{j\in U}\sum_{k\in K} x_{mjpkt} \quad \forall\, p \in P \text{ and } t \in T \tag{4.11}$$

$$\textstyle\sum_{j\in D\cup C}\sum_{k\in K} x_{ijpkt} = G_{ipt} \quad \forall\, i \in B,\ p \in P \text{ and } t \in T \tag{4.12}$$

$$\textstyle\sum_{k\in K}\sum_{i\in R} x_{imqkt} + H_{mqt})/F_{qp} \geq \sum_{k\in K}\sum_{j\in D} x_{mjpk(t+1)} \quad \forall_{T,P,Q,M} \tag{4.13}$$

$$\textstyle\sum_{m\in M}\sum_{k\in K} x_{jmqkt} / A_{pq} \leq \sum_{i\in M}\sum_{k\in K} x_{ijpkt} \quad \forall_{j\in R, q\in Q, p\in P \text{ and } t\in T} \tag{4.14}$$

$$H_{iqt}, x_{ijpkt} \geq 0 \tag{4.15}$$

$$w_{ijkt}, y_{jt} \quad 0 \text{ or } 1, binary \tag{4.16}$$

The codes of mathematical model in ZIMPL software is given at Appendix A.

5. ANALYSIS OF THE MODEL

5.1 Application of the Model with Sample Data

At this section, mathematical model is tested with a sample data set at a Intel® Core ™ i7-5500U processor computer with Zimpl and Scip solver software. The table shows all manufacturing facilities, distribution centers, buyer points, existing and potential collection centers and recovery facilities, and their capacities and fix costs per year of potential collection centers and recovery facilities (Table 5.1).

Table 5.1 : Facilities, capacities and fix costs.

Facility Number	*Center Name*	*Capacities*	*Fix Cost Per Year of Facility*
1	Manufacturing Facility	100,000	-
2	Manufacturing Facility	500,000	-
3	Distribution Center	170,000	-
4	Distribution Center	185,000	-
5	Distribution Center	124,000	-
6	Distribution Center	280,000	-
7	Buyer	-	-
8	Buyer	-	-
9	Buyer	-	-
10	Buyer	-	-
11	Buyer	-	-
12	Buyer	-	-
13	Buyer	-	-
14	Existing Collection Center	10,000	-
15	Potential Collection Center	12,000	1,000
16	Potential Collection Center	35,000	750
17	Potential Collection Center	22,000	1,200
18	Potential Collection Center	20,000	2,000
19	Potential Collection Center	25,000	1,300
20	Potential Collection Center	13,000	800
21	Potential Collection Center	27,000	1,250
22	Existing Recovery Center	12,000	-
23	Existing Recovery Center	13,000	-
24	Potential Recovery Facility	15,000	1,200
25	Potential Recovery Facility	14,500	2,000
26	Potential Recovery Facility	1,600	900
27	Potential Recovery Facility	2,000	950
28	Potential Recovery Facility	5,000	1,100
29	Potential Recovery Facility	35,000	2,700
30	Potential Recovery Facility	15,500	1,700
31	Potential Recovery Facility	9,900	1,300

Table 5.2 shows product and raw material types and their unit volumes and table 5.3 includes unit cost of raw materials of the supplier (Table 5.2 and Table 5.3).

Table 5.2 : Volumes of products and raw materials.

Product / Raw Material Type	***Volume***
1	1
2	2
3	1
4	3
5	1
6	2
7	3

Table 5.3 : Raw materials' unit cost.

Raw Material Type	***Unit Cost***
5	0.75
6	0.6
7	0.53

The table below shows first year's demand and number of end of life products on hand of the customers, the demand and number of end of life products are assumed to increase by 20% every year to show the applicability of the multi-period aspect of the mathematical model (Table 5.4).

Table 5.4 : Demand and number of end of life products.

Buyer Number	Product Type	Demand	Number of End of Life Products
7	2	2,500	1,000
7	3	3,750	2,500
8	1	2,750	500
8	2	1,500	500
8	3	2,500	1,750
9	3	2,000	1,000
9	4	1,750	1,750
10	3	5,000	2,500
10	1	4,000	1,000
10	4	2,750	1,250
11	1	6,000	1,500
11	2	3,500	500
12	4	2,000	600
12	3	3,000	500
13	1	2,700	600
13	4	4,400	1,500

Transportation modes, their capacities, generated amount of CO_2 by using that transportation modes and unit transportation costs of products are summarized below (Table 5.5).

Table 5.5 : Information about transportation.

Transportation Mode	***Vehicle Capacity***	***Genereted CO2***	***Cost Per Unit***
1	2,500	10	0.15
2	3,500	13	0.16
3	4,000	15	0.2

The following table shows relationship between raw materials and products based on their production and recovery requirements (Table 5.6).

Table 5.6 : Relationship between raw materials and products.

Product Type	***Raw Material Type***	***Generated Amount Of Product (F)***	***Required Amount of Raw Material (A)***
1	5	2	1
1	6	3	2
2	5	5	3
2	7	3	2
3	5	2	1
3	6	3	1
3	7	5	3
4	7	4	2

Table 5.7 shows distances between all possible nodes (Table 5.7).

Table 5.7 : The distances among all nodes.

From Node i	*To Node j*	*Distance*	*From Node i*	*To Node j*	*Distance*	*From Node i*	*To Node j*	*Distance*	*From Node i*	*To Node j*	*Distance*
1	3	3	7	14	23	4	14	27	17	31	22
1	4	9	7	15	5	4	15	12	18	22	4
1	5	16	7	16	25	4	16	8	18	23	22
1	6	25	7	17	23	4	17	23	18	24	11
2	3	23	7	18	12	4	18	23	18	25	4
2	4	25	7	19	11	4	19	21	18	26	11
2	5	5	7	20	6	4	20	17	18	27	23
2	6	8	7	21	4	4	21	3	18	28	29
3	7	21	8	14	8	5	14	3	18	29	29
3	8	29	8	15	27	5	15	19	18	30	24
3	9	29	8	16	28	5	16	29	18	31	10
3	10	1	8	17	6	5	17	18	19	22	10
3	11	27	8	18	2	5	18	28	19	23	7
3	12	24	8	19	22	5	19	21	19	24	7
3	13	17	8	20	15	5	20	10	19	25	10
4	7	3	8	21	22	5	21	14	19	26	1
4	8	1	9	14	14	6	14	13	19	27	30
4	9	29	9	15	19	6	15	18	19	28	18
4	10	23	9	16	5	6	16	20	19	29	29
4	11	28	9	17	16	6	17	20	19	30	19
4	12	1	9	18	17	6	18	25	19	31	1
4	13	30	9	19	21	6	19	5	20	22	22
5	7	24	9	20	27	6	20	8	20	23	3
5	8	27	9	21	18	6	21	16	20	24	6
5	9	17	10	14	11	14	22	12	20	25	29
5	10	12	10	15	20	14	23	22	20	26	16
5	11	11	10	16	15	14	24	15	20	27	17
5	12	26	10	17	27	14	25	3	20	28	18
5	13	11	10	18	5	14	26	12	20	29	6
6	7	26	10	19	19	14	27	11	20	30	30
6	8	5	10	20	21	14	28	12	20	31	11
6	9	4	10	21	27	14	29	19	21	22	2
6	10	1	11	14	4	14	30	20	21	23	14
6	11	3	11	15	7	14	31	7	21	24	11
6	12	2	11	16	6	14	28	12	21	25	19
6	13	11	11	17	19	15	22	15	21	26	26
7	3	3	11	18	8	15	23	12	21	27	4
7	4	5	11	19	14	15	24	8	21	28	7
7	5	17	11	20	8	15	25	3	21	29	5
7	6	20	11	21	13	15	26	4	21	30	30
8	3	3	12	14	14	15	27	21	21	31	6

Table 5.8 (continued): The distances among all nodes.

From Node i	*To Node j*	*Distance*	*From Node i*	*To Node j*	*Distance*	*From Node i*	*To Node j*	*Distance*	*From Node i*	*To Node j*	*Distance*
8	4	8	12	15	22	15	28	6	22	1	24
8	5	2	12	16	6	15	29	29	22	2	2
8	6	10	12	17	24	15	30	25	23	1	10
9	3	9	12	18	29	15	31	21	23	2	3
9	4	26	12	19	15	16	22	22	24	1	10
9	5	28	12	20	19	16	23	24	24	2	1
9	6	5	12	21	25	16	24	4	25	1	17
10	3	29	13	14	25	16	25	14	25	2	19
10	4	14	13	15	13	16	26	3	26	1	25
10	5	13	13	16	15	16	27	15	26	2	13
10	6	30	13	17	2	16	28	11	27	1	9
11	3	21	13	18	7	16	29	7	23	2	26
11	4	8	13	19	13	16	30	5	28	1	3
11	5	19	13	20	13	16	31	12	28	2	9
11	6	3	13	21	27	17	22	26	29	1	22
12	3	27	3	14	7	17	23	12	29	2	11
12	4	24	3	15	10	17	24	12	30	1	30
12	5	9	3	16	13	17	25	16	30	2	29
12	6	4	3	17	18	17	26	14	31	1	2
13	3	17	3	18	25	17	27	29	31	2	29
13	4	21	3	19	12	17	28	22	-	-	-
13	5	12	3	20	20	17	29	27	-	-	-
13	6	10	3	21	5	17	30	15	-	-	-

The time horizon is 8 years, also α and β are used as 0.95 and 0.60, the three objective model is applied with four types of products and three types of raw materials and 31 facilities, and objective value is found as 1776910.

5.2 Sensitivity Analysis

After the application of the model, sensitivity analysis is done between increased demand and recovery centers and increased demand and collection centers. First year's aggregate demand (demand of all buyers) is 48100 and it increases by 20% every year during eight years Figure 5.1 and Figure 5.2 show the required number of recovery centers and collection centers.

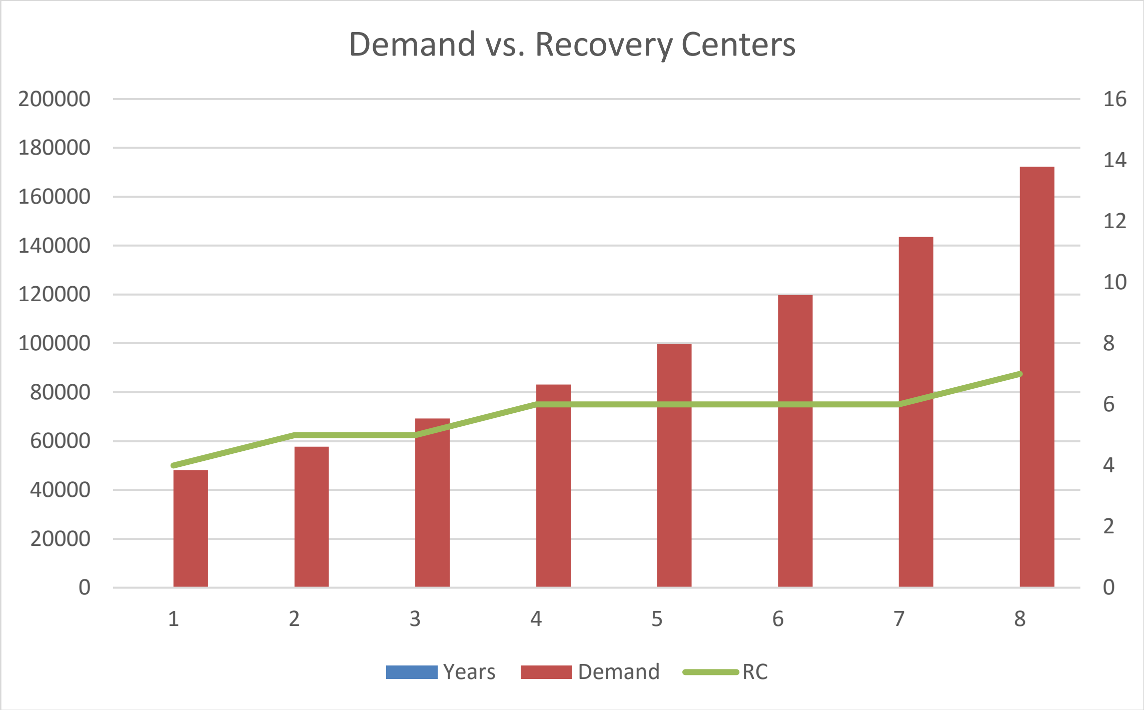

Figure 5.1 : Sensitivity analysis between demand and recovery centers.

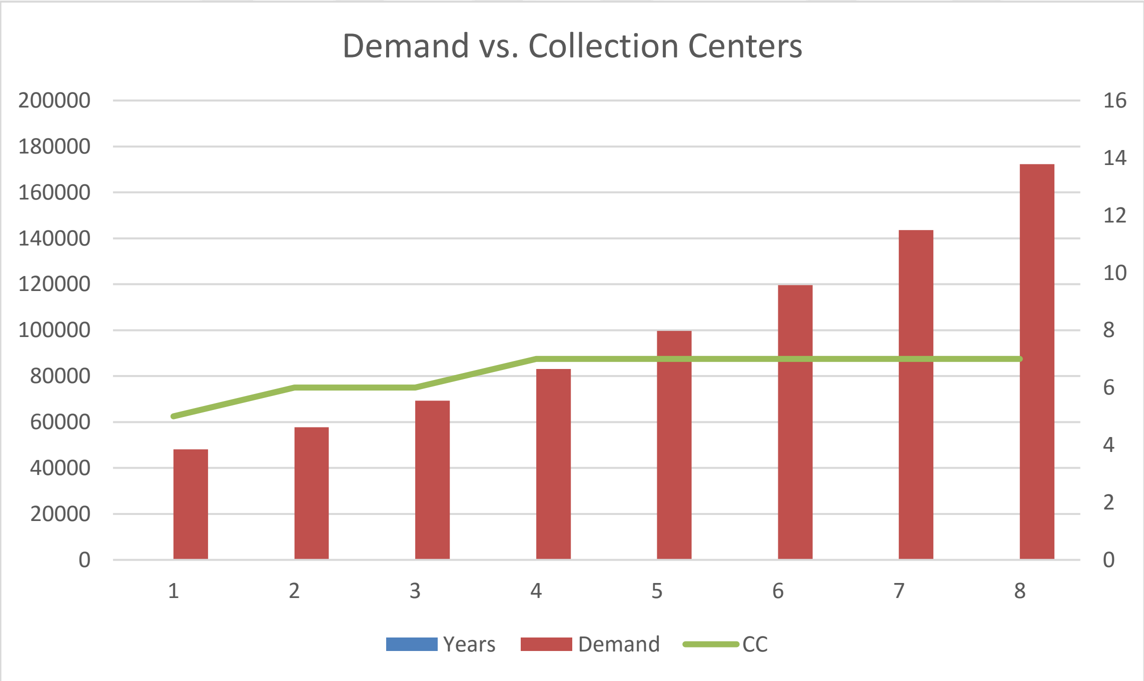

Figure 5.2: Sensitivity analysis between demand and collection centers.

6. CONCLUSION AND RECOMMENDATION

Sustainability and sustainable development gained importance day by day, therefore the encouragement of its governance practices should be continued across the nations, companies, supply chain mananagment, life cycles of products or services etc. Sustainable supply chain management (SSCM) is the management of all flows about information, capital and material as well as cooperation among companies along the supply chain while taking goals from all three dimensions of sustainabity, i.e., economic, environmental and social, into account which are derived from requirements of all stakeholers in the supply chain. In sustainable supply chains, environmental and social criteria need to be fullfilled by the members to remain within the supply chain, while it is expercted that competiveness would be maintained through meeting customer needs and related economic criteria.

This study aims to put forward a sustainable multi-period supply chain network design for minimizing the WEEE which is the one of most crucial sectors in terms of waste management. The contribution of this study is to fill the gap about mathematical closed loop reverse supply chain network design model in multi-product, multi-objective and multi-period aspects of all three dimensions of sustainable development for decision makers.

For the future study, the model should be tested with real data. Moreover, the model can be integrated with the collection and recovery centers that owned by government, so that the companies can compare there options. The main absence of model is the detailed analysis of social dimension of sustainability. Researchers should find another new and real indicators to define social dimension of sustainability, especially for sustainable supply chain management. Also, supply chains and sectors are different from each other, so sectorial snapshots are required, it can be succeed with the new models for the other sectors.

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APPENDICES

APPENDIX A: Codes of the model in zimpl

```
##Recycling sustainability Multi Objective Math Model

##Sets and parameters of the Model

param Alfa := 0.95;
param Beta := 0.60;

param SS := 2;

param Weight1 := 0.33;
param Weight2 := 0.33;
param Weight3 := 0.33;

set B := {read "B.txt" as "<1n>" comment "#"};

set C := {read "C.txt" as "<1n>" comment "#"};

set D := {read "D.txt" as "<1n>" comment "#"};

set K := {read "K.txt" as "<1n>" comment "#"};
param Vcap[K]:= read "K.txt" as "<1n> 2n" comment "#";
param CO2[K]:= read "K.txt" as "<1n> 3n" comment "#";
param TC[K]:= read "K.txt" as "<1n> 4n" comment "#";

set M := {read "M.txt" as "<1n>" comment "#"};

set P := {read "P.txt" as "<1n>" comment "#"};

set PC := {read "PC.txt" as "<1n>" comment "#"};

set PR := {read "PR.txt" as "<1n>" comment "#"};

param FC[PC+PR]:= read "FixCost.txt" as "<1n> 2n" comment
"#";
param S[PC+PR]:= read "FixCost.txt" as "<1n> 3n" comment
"#";

set Q := {read "Q.txt" as "<1n>" comment "#"};
param PCost[Q]:= read "Q.txt" as "<1n> 2n" comment "#";

param V[P+Q]:= read "V.txt" as "<1n> 2n" comment "#";

set PQ := {read "PQ.txt" as "<1n,2n>" comment "#"};
param F[PQ] := read "PQ.txt" as "<1n,2n> 3n" comment "#";
param A[PQ] := read "PQ.txt" as "<1n,2n> 4n" comment "#";
```

```
set RF := {read "RF.txt" as "<1n>" comment "#"};

set BP := {read "BP.txt" as "<1n,2n>" comment "#"};
param Dem[BP]:= read "BP.txt" as "<1n,2n> 3n" comment
"#";
param G[BP]:= read "BP.txt" as "<1n,2n> 4n" comment "#";

set RP := {read "RP.txt" as "<2n,1n>" comment "#"};
param E[RP]:= read "RP.txt" as "<2n,1n> 3n" comment "#";

set U := {read "U.txt" as "<1n,2n>" comment "#"};
param Dis[U]:= read "U.txt" as "<1n,2n> 3n" comment "#";

set ALL := {read "ALL.txt" as "<1n>" comment "#"};
param Cap[ALL]:= read "ALL.txt" as "<1n> 2n" comment "#";

set T := {read "T.txt" as "<1n>" comment "#"};

set UPK := U*P*K;

set UPQK:= U*(P+Q)*K;

set UK  := U*K;

set MQ := M*Q;

##Decision Variables

var X[UPQK*({0}+T)] >= 0;
var Y[ALL*T] binary;
var W[UK*T] binary;
var H[MQ*({0}+T)] >= 0;

##Constraints

subto CapacityCons: forall <j,t> in ALL*T do
     sum <i,j,p,k> in UPK : V[p]*X[i,j,p,k,t] <=
Cap[j]*Y[j,t];

subto DemandCons: forall <j,p,t> in BP*T do
     sum <i,j,p,k> in UPK : X[i,j,p,k,t] >=
Dem[j,p]*(1+(t*0.2));

subto CollectCons: forall <i,p,t> in BP*T do
     sum <j> in D+PC+C : sum <k> in K : X[i,j,p,k,t] ==
G[i,p]*(1+(t*0.2));

subto OpenCons: forall <j,t> in (M+D)*T do
     Y[j,t]==1;
```

```
subto BeginCons: forall <j,t> in M*{0} do
     sum <i,q,k> in (PR+RF)*Q*K : X[i,j,q,k,t] == 0;

subto BalanceConsD: forall <m,p,t> in D*P*T do
     sum <i> in M : sum <p,k> in P*K : Alfa *
X[i,m,p,k,t] == sum <j,p,k> in BP*K : X[m,j,p,k,t];

subto BalanceConsDC: forall <m,p,t> in D*P*T do
     sum <i> in B : sum <p,k> in P*K : Alfa *
X[i,m,p,k,t] == sum <j,p,k> in (PC+C)*P*K : X[m,j,p,k,t];

subto BalanceConsC: forall <m,p,t> in (PC+C)*P*T do
     sum <i> in D+B : sum <p,k> in P*K : Alfa *
X[i,m,p,k,t] == sum <j,p,k> in (RF+PR)*P*K :
X[m,j,p,k,t];

subto VehicleCapCons: forall <i,j,k,t> in UK*T do
     sum <p> in P+Q : X[i,j,p,k,t] * V[p] * SS / 52 <=
Vcap[k] * W[i,j,k,t];

subto RegulationCons: forall <t> in T do
     sum <i> in C+PC: sum <j> in PR+RF: sum <p,k> in P*K:
X[i,j,p,k,t] >= Beta * sum <i> in B: sum <j> in C+PC+D:
sum <p,k> in P*K: X[i,j,p,k,t];

subto PurchaseCons: forall <m,p,q,t> in M*PQ*T do
     (sum <i> in PR+RF : sum <k> in K : X[i,m,q,k,t-1] +
H[m,q,t-1]) / F[p,q] >= sum <j> in D : sum <k> in K :
X[m,j,p,k,t];

subto RecyclingCons: forall <j,p,q,t> in (PR+RF)*PQ*T do
     sum <m,k> in M*K : X[j,m,q,k,t] / A[p,q] <= sum
<i,k> in (PC+C)*K : X[i,j,p,k,t];

##Objective Functions

minimize objective: Weight1 * (sum <j,t> in (PC+PR)*T :
FC[j]*Y[j,t] + sum <m,q,t> in MQ*({0}+T) :
PCost[q]*H[m,q,t] + sum <j,p,i,k,t> in RP*(PC+C)*K*T :
E[j,p]*X[i,j,p,k,t] + sum <i,j,p,k,t> in UPK*T :
TC[k]*X[i,j,p,k,t]*Dis[i,j]*SS)
                         +Weight2 * (sum <i,j,k,t> in
UK*T: W[i,j,k,t]*Dis[i,j]*CO2[k]*SS)
                         -Weight3 * (sum <j,t> in
(PC+PR)*T : S[j]*Y[j,t]);
```

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PUBLICATIONS, PRESENTATIONS AND PATENTS ON THE THESIS:

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