DOKUZ EYLÜL UNIVERSITY
GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES

# MODELLING STRATEGIC AND TACTICAL PLANNING PROBLEMS IN CLOSED-LOOP SUPPLY CHAINS UNDER CRISP AND FUZZY ENVIRONMENTS

by
Kemal SUBULAN

June, 2012
İZMİR

# MODELLING STRATEGIC AND TACTICAL PLANNING PROBLEMS IN CLOSED-LOOP SUPPLY CHAINS UNDER CRISP AND FUZZY ENVIRONMENTS

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**by**
**Kemal SUBULAN**

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**M.Sc THESIS EXAMINATION RESULT FORM**

We have read the thesis entitled **"MODELLING STRATEGIC AND TACTICAL PLANNING PROBLEMS IN CLOSED-LOOP SUPPLY CHAINS UNDER CRISP AND FUZZY ENVIRONMENTS"** completed by **KEMAL SUBULAN** under supervision of **ASST. PROF. DR. A.SERDAR TAŞAN** and we certify that in our opinion it is fully adequate, in scope and in quality, as a thesis for the degree of Master of Science.

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**MODELLING STRATEGIC AND TACTICAL PLANNING PROBLEMS IN CLOSED-LOOP SUPPLY CHAINS UNDER CRISP AND FUZZY ENVIRONMENTS**

## ABSTRACT

Nowadays, there has been a growing interest in recovery options such as recycling, remanufacturing and reusing in the scope of Reverse Logistics (RL) and Closed-Loop Supply Chain (CLSC) concepts due to the environmental, economical issues and legal obligations. Due to this fact, companies should take into account the utilized recovery option while preparing both strategic planning and tactical planning activities. On the other hand, there are lots of studies in the literature related to the RL and CLSC network design problem which takes place in strategic planning level but a few of them handles the tactical planning processes. However, multi-objective RL and CLSC network design models are rarely discussed in the literature. For filling these gaps, three mathematical models namely Model I, II and III are proposed in this thesis. A multi-objective, multi-echelon and multi-product mixed integer linear programming Model I is developed for a lead/acid battery CLSC in fuzzy environment. In addition to minimize total costs of the CLSC, an unhandled objective (maximize collection of spent batteries) is taken into account based on the well known maximal coverage problem. Furthermore, new flexibility criteria namely total recycling and collection volume flexibility are added to the third objective function, total volume flexibility. A holistic strategic planning Model II with two objectives namely maximization of total CLSC profit and minimization of total environmental impact along the CLSC network is developed for a tire collection and recovery system considering multiple recovery options and time periods. A fuzzy mixed integer programming Model III is proposed for medium-term planning in a CLSC related to a conceptual product with remanufacturing option. Since the real world CLSCs are surrounded with uncertainty, capacities, demands, return rates, acceptance ratios, available production/remanufacturing times, transportation upper bounds and objective function value are considered as fuzzy.

**Keywords:** Reverse logistics, closed-loop supply chain network design, fuzzy goal programming, battery recycling, eco-indicator 99 methodology, end-of-life tire recovery, interactive fuzzy goal programming, Taguchi approach, tactical planning, remanufacturing.

**KAPALI ÇEVRİM TEDARİK ZİNCİRLERİNDE STRATEJİK VE TAKTİKSEL PLANLAMA PROBLEMLERİNİN BELİRLİ VE BULANIK ORTAMLARDA MODELLENMESİ**

# ÖZ

Günümüzde, çevresel, ekonomik konular ve yasal zorunluluklar nedeniyle Tersine Lojistik (TL) ve Kapalı Çevrim Tedarik Zinciri (KÇTZ) kavramları kapsamında yeniden imalat, geri dönüşüm ve yeniden kullanım gibi geri kazanım alternatiflerine artan bir ilgi görülmektedir. Bu gerçek ışığında, işletmeler hem stratejik hem de taktiksel düzeyde aktivitelerini planlarken kullanılan geri kazanım opsiyonunu dikkate almalıdırlar. Öte yandan, literatürde stratejik planlama düzeyinde yer alan TL ve KÇTZ ağ tasarım problemine ilişkin birçok çalışma bulunmasına karşın, bunlardan çok azı taktiksel planlama aktivitelerini konu edinmektedir. Diğer yandan, literatürde çok amaçlı TL ve KÇTZ ağ tasarım modellerinin sayısı da oldukça sınırlıdır. Literatürdeki bu boşlukları gidermek üzere bu tez kapsamında Model I, II ve III olmak üzere üç farklı matematiksel model önerilmiştir. Model I, bir kurşun/asit akü KÇTZ'ne ilişkin ağ tasarım problemi için bulanık ortamda geliştirilmiş çok amaçlı, çok aşamalı ve çok ürünlü karma tamsayılı programlama modelidir. KÇTZ'ne ilişkin toplam maliyetin en küçüklenmesinin yanı sıra, daha evvel ele alınmamış bir amaç (açılan tesisler tarafından toplanacak kullanılmış akü miktarının en büyüklenmesi) literatürde iyi bilinen en büyük kapsama problemine (maximal covering problem) dayanılarak ele alınmıştır. Ayrıca tersine akışlardan ötürü, yeni esneklik kriterleri, toplam geri dönüşüm ve toplama esneklikleri üçüncü amaç fonsiyonu olan toplam miktar esnekliğine eklenmiştir. Model II, ömrünü tamamlamış lastiklere ilişkin KÇTZ'ndeki toplam karın en büyüklenmesi ve KÇTZ boyunca oluşan toplam çevresel etkinin en küçüklenmesini amaçlayan, birden çok geri kazanım alternatifini ve zaman periyodunu dikkate alan bütünsel bir stratejik planlama modelidir. Ayrıca, kavramsal bir ürüne ilişkin KÇTZ'ndeki orta dönem planlanma problemi için yeniden imalat opsiyonu dikkate alınarak bir bulanık karma tamsayılı programlama modeli (Model III) geliştirilmiştir. Gerçek hayattaki KÇTZ'leri birçok belirsizlikle çevrili olduğu için, kapasiteler, talepler, haftalık üretim/yeniden imalat süreleri, taşımalara ilişkin üst sınırlar, geri dönüşüm yüzdeleri ve geri dönen ürünler için kabul edilme oranları bulanık veri olarak ele alınmıştır.

**Anahtar sözcükler:** Tersine lojistik, kapalı çevrim tedarik zinciri ağ tasarımı, bulanık hedef programlama, akü geri dönüşümü, eco-indicator 99 methodolojisi, ömrünü tamamlamış lastiklerin geri kazanımı, etkileşimli bulanık hedef programlama, Taguchi yaklaşımı, taktiksel planlama, yeniden imalat.

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# CHAPTER ONE
# INTRODUCTION

## 1.1 Background

Reverse Logistics (RL) and Closed-Loop Supply Chains (CLSCs) have becoming an important issue for both researchers and practitioners in the last decade because of increasing economical competitive, regulatory pressures and customer expectations. In the other words, increased environmental and economical issues related to the discarded products and legal regulations generated by the governments have been putting pressure on many manufacturing firms about the production, distribution, collection, recovery and disposition of the products in an environmentally way. In addition to the environmental factors and laws, many companies and organizations are aware of the revenue obtained from the product recovery for their sustainability. Therefore, RL activities, efficient strategic and tactical planning procedures of CLSCs and product recovery systems have been much more interested issues throughout this decade. Due to this fact, companies should take into account the utilized recovery option or RL activities such as reusing, refurbishing, recycling and remanufacturing etc. while preparing their long range (strategic) and medium-term (tactical) planning processes.

Looking at the basic definitions and main features of these concepts, RL & CLSC management are reviewed as follows: Rogers and Tibben-Lembke (1999) defined RL as “the process of planning, implementing and controlling the efficient, cost-effective flow of raw materials, in-process inventory, finished goods and related information from the point of consumption to the point of origin for the purpose of recapturing value or proper disposal” (p. 2). In contrast to RL, CLSCs involve not only the reverse flows of the materials/goods from the end users to the manufacturers or related facilities such as collection centers, disposal sites and recovery centers but also the forward flows of raw materials/goods from suppliers to manufacturers and then to the end users.

Atasu, Guide, and Van Wassenhove (2008) described CLSC management as “the design, control and operation of a system to maximize value creation over the entire life-cycle of a product with dynamic recovery of value from different types and volumes of returns over time” (p. 483). CLSCs cover the traditional forward supply chain activities with the additional activities related to the reverse flows. These activities can be explained as follows (Guide, Harrison, and Van Wassenhove, 2003):

- Collection/acquisition of used products from the end-users.
- Tranportation and also warehousing of these used products from the points of use to a point(s) of disposition.
- Classification, controlling and inspection in order to determine the product’s condition for selecting the most economic or the best recovery option.
- Selection of the right recovery option: direct reuse, refurbish, repair, remanufacture, recycle or disposal.
- Sales and distribution of these refurbished/remanufactured products to the new or secondary markets.

According to these general definitions, both forward logistics activities and RL activities have been included as an important issue in CLSC management. For this reason, we can say that RL activities play an important role on the success and efficiency of integrated supply chain management. Thus, this integration is required for supply chain planning in both strategic and tactical levels.

In literature, some important properties, advantages and disadvantages of RL & CLSC concepts and related planning procedures were emphasized by the researchers as follows:

- Strategic planning problem (network design) in CLSCs is applicable for the remanufacturable/refurbishable products that have high recoverable value, long product life cycles and well-established forward flows (Uster, Easwaran, Akcali, and Cetinkaya, 2007). This implies that well-established forward supply chain configuration is a pre-requisite for managing and integrating forward and reverse flows effectively.

- With a well-managed CLSC, one of the most important steps of sustainable development which interests both economics aspects and the other aspects such as environment and sustainability of natural resources can be exceeded (Lee, Dong, and Bian, 2010). It is also highlighted that RL has become icreasingly important as a profitable and sustainable business strategy by Du and Evans (2008).
- Karabulut (2009) categorized the benefits of RL into four topics: economic gain, improved market position, better customer relationships, market and asset protection.
- Effective and efficient management of RL activities can increase companies' customer service levels while reducing their costs. In other words, effective management of RL and product recovery activities provides important cost savings in acquisition, production, disposal, inventory, transportation and increases the constancy of the existed customers.
- Integrating the forward and reverse flows results in benefits. For instance, equipment, facilities and personnel can be shared by both forward and reverse logistics activities. This provides synergy in terms of reduced costs and improved service levels (Stock, 2001).
- The environmental side of RL activities enforces company to gain new customers with environment consciousness.
- Designing the RL & CLSC networks as a strategic decision provides the inputs of the tactical and operational decisions (Subulan and Tasan, 2011a, 2011b).
- In a CLSC, integrating the forward and reverse channels is challenging task and important part of the decision making process (Fleischmann, Krikke, Dekker, and Flapper, 1999).
- Uncertainty emerged in all aspects of the CLSC design problem. For instance, uncertainty in timing, quantity and quality of returns, uncertainty in materials recovered, routing uncertainty and processing time uncertainty (Kumar and Malegeant, 2006).

- CLSC planning acts like a combinatorial problem whose computation time to yield an optimal solution increases exponentially when the problem size grows (Sim, Jung, Kim, and Park, 2004).
- Complexity in CLSCs is generally higher than the open loop supply chains (Amin and Zhang, 2012). This complexity comes from the reverse supply chains due to the new coordination issues (Krikke, Le Blanc, and Van De Velde, 2004).

In the light of all this above information, there are lots of studies in the literature related to the RL & CLSC network design problem which takes place in strategic planning level but so few handles the tactical planning activities in their developed quantitative model. Furthermore, production-distribution planning process is more complex when recovery options and corresponding reverse flows are involved because of the complicating characteristics such as uncertainty in timing, quality and quantity of returned products as discussed by Guide Jr. (2000). Moreover, there is a lack of multi-objective optimization models in the literature of RL & CLSC network design problem which considers different objectives except only cost or profit orientation such as maximizing amounts of collected products under scarce financial resources for fixed collection investments, accordingly maximizing reverse service levels (maximizing responsiveness of reverse supply chain), minimizing the environmental impact along the CLSC network and maximizing the volume flexibility of a CLSC regarding production, distribution, collection and recovery activities. There are also a few studies which present holistic mathematical models that involve wide range of modelling characteristics such as consideration of multiple recovery options, multi-objectivity, reverse bills of material (BOM), dynamic returns, dynamic location, environmental issues, uncertainty in demand, capacities and product returns, production technology and transportation mode selection etc. for better reflection of real life applications. Our research meets these requirements via developed mixed integer linear programming (MILP) models (Model I, II and III) under crisp and fuzzy environments.

## 1.2 Scope of the Thesis

Research motivation of this thesis depends on the need of developing novel mathematical models for complex CLSCs via MILP. Since these complex RL & CLSC networks are surrounded with uncertainty, we developed three MILP models in fuzzy environment. Two of these models can be used as strategic planning tools and depend on case studies: inspired from the lead/acid battery industry and tire industry, respectively. In the final model, a generic tactical planning model is developed for a CLSC with remanufacturing option under uncertainty. Definition and detail explanations related to these three models can be stated as follows:

**Model I:** Fuzzy multi-objective optimization model for strategic planning problem of a lead/acid battery CLSC (Subulan, Tasan, and Baykasoglu, 2012a).

*Goals:*

1. Minimization of total CLSC costs.
2. Maximization of total coverage related to the scrap battery collection.
3. Maximization of total volume flexibility.

*Given:*

- cost parameters such as fixed set-up, production, transportation, material purchasing, scrap battery purchasing, recycling, collection and disposal costs and revenues obtained by scrap battery sales,
- demand data and corresponding return fractions,
- recycling and disposal rates,
- distances between each stage and maximum allowable distances,
- weights of the different battery types and reverse BOMs,
- production, recycling and vendor capacities,
- distribution/collection capacities of regional wholesalers, collection centers and hybrid facilities,

- weight factors for capacity utilizations of battery manufacturers, licensed recycling facilities, regional wholesalers, collection centers and hybrid facilities.

*Determine:*

- locations of opened regional wholesalers, collection centers, hybrid facilities and licensed recycling facilities,
- production and recycling quantities of each battery type in each battery manufacturer and licensed recycling facility, respectively,
- distribution and collection quantities of brand new batteries and scrap batteries, respectively,
- material purchasing quantities from the vendors,
- material quantities obtained by recycling way,
- spent battery purchasing quantities from the external scrap dealers,
- amounts of spent battery sales to the external scrap dealers,
- allocation of battery dealers to regional wholesalers or hybrid facilities,
- allocation of battery dealers to collection centers or hybrid facilities,
- sell or buy decisions related to spent batteries.

*Case study:* derived from a lead/acid battery CLSC in Turkey.

*Used methodologies:*

- mixed integer linear programming,
- fuzzy goal programming approach with different importance and priorities (FGP-DIP),
- fuzzy AHP method,
- group decision making approach.

**Model II:** Multi-objective optimization model for strategic planning problem of a tire CLSC with multiple recovery options and time periods (Subulan, Tasan, and Baykasoglu, 2012b).

*Goals:*

1. Maximization of total profit of overall CLSC.
2. Minimization of total environmental impact throughout the CLSC.

*Given:*

- selling and discount selling price of different brand new tire families with/without any end-of-life tire returns,
- selling prices of retreaded, scrap tires and recycled materials,
- monetary parameters such as fixed set-up, rental and operating, production, remanufacturing, recycling, technology investment, transportation, material purchasing, capacity expansion, collection, inventory and disposal costs,
- parameters related to environmental impacts during material purchasing, production, transportation, warehousing, end-of-life collection and processing, energy recovery, remanufacturing, recycling and disposal,
- demand data for primary and secondary markets, corresponding return rates and return volumes,
- recycling, remanufacturing and disposal fractions,
- weights of the tires and reverse BOM,
- storage capacity consumption factors for tires and materials and regarding storage capacities,
- production, remanufacturing and recycling quantities by using different environmental protection technologies,
- module capacities for storage and inbound handling,
- minimum throughputs for opening of facilities,
- transportation capacities of different truck types and distances between each stage of the CLSC.

*Determine:*

- location of opened facilities such as distribution centers, centralized return points, retreading companies and tire recycling facilities by period,
- allocation of shipments from collection centers to centralized return points with a single vehicle type by period,
- selection of environmental protection technologies by new tire plants, retreading companies and tire recycling facilities,
- integration of different module types to distribution centers and centralized return points for capacity expansions,
- production, retreading and recycling quantities of different tire families by using selected environmental protection technology, and by period,
- amounts of purchased materials from external suppliers,
- transportation quantities between the several stages of the CLSC by vehicle type and by period,
- inventory holding levels at new tire plants, distribution centers and centralized return points.

*Case study:* inspired from tire industry case in Aegean Region of Turkey.

*Used methodologies:*

- mixed integer linear programming,
- eco-indicator 99 methodology, a Life Cycle Analysis (LCA) based method,
- interactive fuzzy goal programming approach,
- Taguchi Design of Experiment (DOE) approach.

**Model III:** A generic medium-term (tactical) planning model for a CLSC with remanufacturing option (Subulan, Tasan, and Baykasoglu, 2012c).

*Goal:* Minimization of total costs of the CLSC.

*Given:*

- cost parameters such as production, remanufacturing, collection, transportation, inventory carrying, tardiness, penalty and disposal,
- weekly fuzzy demands of wholesalers and retailers for each product type,
- fuzzy available time for production and remanufacturing in each week,
- fuzzy return rates for product returns to wholesalers and retailers, respectively,
- fuzzy conformity rate for remanufacturing processes,
- required time for producing and remanufacturing one unit of product,
- fuzzy capacities for storage activities of remanufacturing facilities and collection centers,
- fuzzy transportation upper bounds,
- distances between several stages of the CLSC.

*Determine:*

- production and remanufacturing quantities of different product types during each week,
- collection and distribution quantities between the several stages by period,
- inventory holding levels at manufacturing plants, wholesalers, collection centers and remanufacturing facilities by period,
- quantity of tardy products at wholesalers and retailers level by period,
- quantity of products that are not delivered to the wholesalers and retailers at the end of planning horizon.

*Used methodologies:*

- Different fuzzy solution approaches for fuzzy mixed integer programming.
    - Zimmermann's approach max-min operator,
    - Zimmermann's approach convex combination of the min-operator and max-operator,

- Werner’s approach fuzzy-and operator,
- Li’s two-phase approach.

Due to the ambiguity in determining the target values and desirable achievement degrees of the goals; capacity, demand, returns and other parameters of the real life CLSCs, fuzzy mathematical programming approach is employed in all model development phases.

### 1.3 Reseach Goals and Motivations of the Thesis

The main purpose of this thesis is to develop new quantitative models for complex CLSCs via mathematical modelling approach and to solve them under crisp and fuzzy environments. This complexity comes from the more applicable and realistic issues such as multi-objective nature, availability of multiple recovery options for a closed-loop system, dynamic design decisions, group decision making environment, uncertain data structure etc. in real world problems.

The objectives and sub-objectives of this thesis can be classified for each Chapter as follows:

1. Present a detail overview on definitions of RL & CLSC management, main concepts in RL & CLSC management, categories of RL flows (source of reverse flows) and other issues such as environmentally conscious manufacturing, green logistics and sustainable supply chains (Chapter 2).
2. Present a literature review on RL & CLSC network design problem and main modelling characteristics in RL & CLSC network design (Chapter 3).

3.1 Develop a multi-objective, multi-echelon and multi-product strategic planning model for a lead/acid battery CLSC.

3.2 Formulate new objectives such as coverage maximization for collection activities and volume flexibility maximization regarding collection-recovery system in the developed model.

3.3 Present an application of fuzzy goal programming approach with different importance and priorities (FGP-DIP) developed by Chen and Tsai (2001).

3.4 Propose a new method in order to obtain desirable achievement degree of each fuzzy goal based on weighted geometric mean. This method will be designed to use in group decision making environment where the importance/weights and the index of optimism (such as moderate, optimistic and pessimistic) of each group member is different (Chapter 4).

4.1 Develop a multi-objective, multi-echelon, multi-product and multi-period logistics network design model for a tire CLSC while taking into account the multiple recovery options and environmental issues. With its holistic view, this model yields both profit and ecological oriented configuration.

4.2 Apply eco-indicator 99 method to quantify the environmental performance throughout the CLSC network.

4.3 Solve the model in fuzzy environment by employing interactive fuzzy goal programming approach.

4.4 Analyze both main effects and simultaneous effects of some parameters on the objective functions via Taguchi DOE technique (Chapter 5).

5.1 Develop a multi-echelon, multi-product, multi-period generic medium-term planning (MTP) model for the CLSC of a conceptual product considering remanufacturing as a recovery option via fuzzy mixed integer programming.

5.2 Formulate the conversion of fuzzy non-linear constraints whose right hand values involve fuzzy parameters into the linear crisp equivalent.

5.3 Transform the proposed fuzzy mathematical program by using different fuzzy aggregation operators and compare the results for providing more confident solution for the decision maker.

5.4 Consider the return rate and acceptance ratio as fuzzy data for product returns in order to overcome the uncertainty in quality and quantity of returned products (Chapter 6).

## 1.4 Structure of the Thesis

This thesis consists of seven Chapters and further organized as follows. In Chapter 1, a general overview of RL and CLSCs with their needfulness, properties, advantages and disadvantages are given in the background section. Then, goals, motivations, scope and structure of the thesis are presented.

In Chapter 2, general definitions of RL & CLSC and detail explanations related to basic issues in RL and CLSC management such as recycling, remanufacturing, refurbishing, environmental conscious manufacturing, green logistics and sustainable supply chains etc. are given.

In addition to relevant literature sections of Chapters 4, 5 and 6, a comprehensive literature review on RL & CLSC network design problem is given in Chapter 3. This general review can be divided into three parts: (i) solution approaches to these network design problems such as mixed integer programming, decomposition methods and heuristic based methodologies; (ii) modelling approaches for uncertainty such as stochastic, possibilistic etc. and finally (iii) selective overview of main modelling features in RL & CLSC network design.

Chapter 4 begins with its own introduction section and goes on with literature review on multi-objective optimization of RL & CLSC network design problem and applications of FGP-DIP. Details of the problem with the notation, model parameters, decision variables and mathematical model formulation are described in section 4.4. In section 4.5, proposed model is applied to a case study inspired from lead/acid battery sector in Turkey for depicting the validity and practicality of the proposed model. Efficient compromise solution of the proposed model with the satisfaction of multiple fuzzy goals is also achieved by using ILOG OPL Studio version 6.3 optimization solver in the same section. Section 4.6 demonstrates the fuzzifing of the proposed strategic planning model. This section also contains the construction of the membership functions, determination of desirable achievement degrees for all fuzzy objectives by using linguistic variables and transformation of the fuzzy model to the equivalent crisp mathematical formulation. Sensitivity analysis of the proposed model is also presented considering different scenarios in section 4.7. Finally in section 4.8, Chapter conclusion and future works are given.

Similarly, Chapter 5 starts with its own introduction and organized as follows. In section 5.3, applications of eco-indicator 99 methodology in supply chain network design and planning are reviewed. In section 5.4, details of the problem with the model formulation, assumptions and model parameters are described. Then in section 5.5, application of the proposed model to an illustrative example inspired by Turkey case is discussed. This section also involves the detail explanations related to the solution methodology, interactive fuzzy goal programming. In section 5.6, evaluation of the computational results through Taguchi experimental design method is performed. In section 5.7, Chapter conclusion and suggestions for the future researches are given respectively.

In Chapter 6, after the introduction part, literature review on tactical planning problem in CLSCs is given. In section 6.4, problem description with network representation of the MTP problem, assumptions, notation and mathematical model formulation are presented. In section 6.5, fuzzy medium-term planning (FMTP) problem is discussed and also this section involves the construction of the membership functions for the fuzzy goal and constraints which have fuzzy minimum, fuzzy maximum and fuzzy equal characteristics, also the transformations of the fuzzy model into the crisp equivalent mathematical programs are included in the same section. In section 6.6, proposed model is illustrated through a basic example for depicting the validity and practicality. In section 6.7, in order to investigate the sensitivity of the model and analyze the sensitivity of decision parameters regarding collection-remanufacturing system to variation of satisfaction degrees and objective value, the proposed FMTP problem is resolved with different target values of acceptance rate (%), unit remanufacturing cost ($), transportation upper bound (units) on remanufactured products and total weekly available time for remanufacturing (hours). Finally in section 6.8, Chapter conclusion and future works are given.

In Chapter 7, an overall summary, conclusion and contributions of this thesis are listed with future research directions and potential extensions for the developed models.

# CHAPTER TWO
# DEFINITIONS AND MAIN CONCEPTS OF REVERSE LOGISTICS & CLOSED-LOOP SUPPLY CHAIN MANAGEMENT

## 2.1 Basic Definitions of RL and CLSC

RL and CLSCs are classified as main issues under environmentally conscious manufacturing and product recovery topic and the importance of these issues have been growing due to the strict environmental regulations and diminishing raw material resources (Ilgin and Gupta, 2010). There are various definitions and explanations related to RL and CLSC concepts in the literature. Therefore, some of the most popular definitions of RL can be reviewed as follows:

According to the Council of Logistics Management (CLM), RL is often used to refer to "the role of logistics in recycling, waste disposal, and management of hazardous materials"; a broader perspective includes all issues related to logistics activities carried out in source reduction, recycling, substitution, reuse of materials and disposal (Fleischmann, 2000, p.5; Stock, 1992). A more comprehensive definition of RL is given by Stock (1998) again. According to his new definition, RL refers to "the role of logistics in product returns, source reduction, recycling, materials substitution, reuse of materials, waste disposal and refurbishing, repair and remanufacturing when looked from the business logistics perspective; it is referred to as RL management and is a systematic business model that applies best logistics engineering and management methodologies across the enterprise in order to profitably close the loop on the supply chain when looked from the engineering logistics perspective" (Daugherty, Myers, and Richey, 2002, p. 86). Second definition is more explicative since including all RL activities, well announced goals and different perspectives.

Pohlen and Farris (1992) defined RL as "the movement of goods from a consumer towards a producer in a channel of distribution" (p. 35). In this definition, only the transportation activities regarding reverse flows are emphasized.

Kroon and Vrijens (1995) explained RL as "the logistics management skills and activities involved in reducing, managing and disposing of hazardous or non-hazardous waste from packaging and products" (Zuluaga and Lourenço, 2002, p. 3).

Fleischmann et al. (1997) expressed RL as "a process which encompasses the logistics activities all the way from used products no longer required by the user to products again usable in a market". Fleischmann (2001) gave more detailed definition of RL as "the process of planning, implementing and controlling the efficient, effective inbound flow and storage of secondary goods and related information opposite to the traditional supply chain directions for the purpose of recovering value and proper disposal".

According to Rogers and Tibben-Lembke (1999), RL is "process of planning, implementing, and controlling the efficient, cost-effective flow of raw materials, in-process inventory, finished goods and related information from the point of consumption to the point of origin for the purpose of recapturing value or proper disposal" (p. 2).

A narrow definition of RL is given by Krikke (1998) as "the collection, transportation, storage and processing of discarded products".

Dowlatshahi (2000) defined RL as "a process in which a manufacturer systematically accepts previously shipped products or parts from the point of consumption for possible recycling, remanufacturing or disposal" (Zuluaga and Lourenço, 2002, p. 3).

Finally, Reverse Logistics Association (RLA) defined RL as "all activity associated with a product/service after the point of sale, the ultimate goal to optimize or make more efficient aftermarket activity, thus saving money and environmental resources" (RLA, n.d.).

Opposite to the previously mentioned definitions, CLSCs not involve only the reverse flows and RL activities but cover all of these issues and definitions. According to Ilgin and Gupta (2010), there are high level interdependence relationships between the forward and reverse logistics activities. For this reason, simultaneous consideration of forward and reverse flows is required for more cost effective management of RL operations. Some other definitions or explanations related to the CLSCs are given as follows:

CLSCs contain two distinct supply chains namely forward and reverse. Forward supply chains usually represent the flow of products from the manufacturer to customer while the reverse supply chains undertake the flow of used scrap products from the customer to the recovery centers such as remanufacturer, recycler etc. These two separate flows are closed by a recovery operation such as remanufacturing (Ostlin, Sundin, and Björkman, 2008).

Coyle, Langley, Gibson, Novack, and Bardi (2009) also defined CLSC as “consideration of both forward and reverse flows processes in a supply chain for designing and managing these flows explicitly”.

Another definition is made by Bijulal and Venkatesvaran (2008) as “the forward and reverse supply chain activities for the whole life cycle of the products” (p. 1). The integration of the forward and reverse supply chains together establishes the basics of a CLSC. A CLSC consists of the manufacturing facilities, the collection point for used returned products, system for inspection or control and then application of a suitable recovery operation on the confirmed used items in a recovery facility.

The main differences between the closed loops and open loops are explained by Krikke (1998): in closed-loop systems, reverse flows have a direct connection with the original forward flows activities. However, reverse supply chain may be connected to alternative forward supply chains through intermediate markets in open loops. Another important difference between the forward and closed-loop supply chains is that the customer act like both a customer for recovered products and as a supplier to the recovery centers or remanufacturing facilities since they account for the source of used product returns (Krikke et al., 2004).

According to Sim et al. (2004), CLSCs distinguish from the RL as a new concept since RL does not treat only the return processes as well as involves the supply chain management operations. Three main flows in CLSCs are categorized by Debo, Savaskan, and Van Wassenhove (2002) as material flows, information flows and financial flows, respectively.

Key drivers of RL & CLSC management are tried to be explained in Figure 2.1.

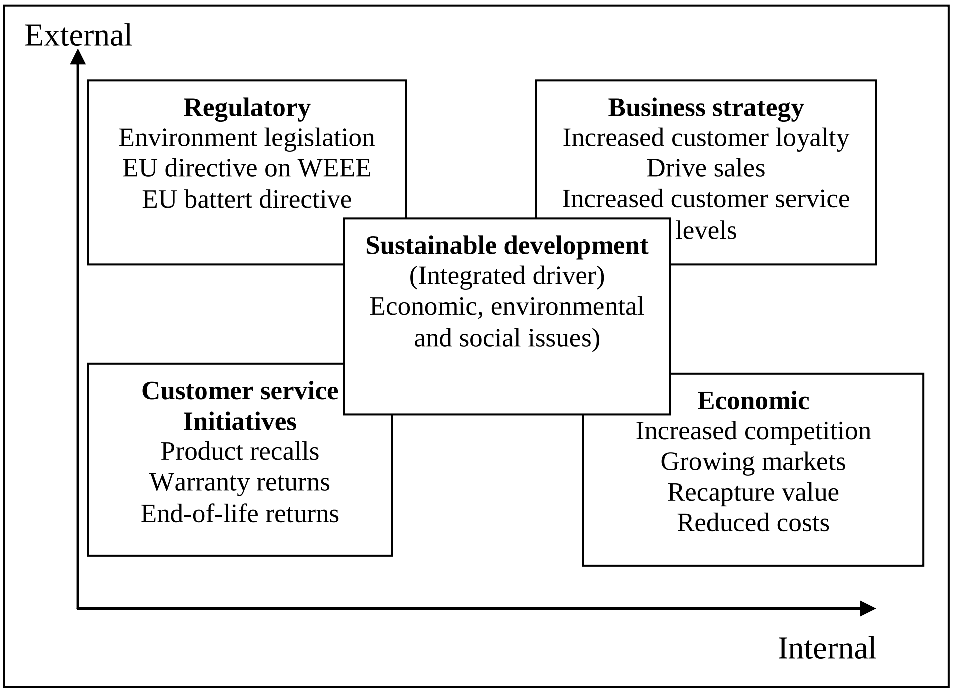



Figure 2.1 Business drivers of RL (adopted from Subramaniam, 2009; Zheng, 2011; Srivastava and Srivastava, 2006)

## 2.2 Main Sources of Product Returns

Different categories of reverse flows or return reasons can be explained as follows (Brito and Dekker, 2002, 2003; Fleischmann, 2000):

(i) *Manufacturing returns:* This return type comes from the production processes. Raw materials may be left over, semi-finished or final goods may fail quality checks and have to be reprocessed and products may be left over during production phase (Brito and Dekker, 2002). Quality control returns, production leftovers, raw material surplus can be given as examples.

(ii) *Product recall:* In some situations, defective products can be recognized after these products entered their regarding supply chain. For this reason, they are recalled back from the chain (Karaçay, 2005). The main reasons of this type of returns are the safety or health problems with the products (Brito and Dekker, 2002). In other words, the general reason of this return type is discovery of safety issues. As well as cost of the replacing the recollected product or paying for damage caused by use, there exist other major costs due to damaging the brand name and decreasing the trust in producer. For instance, several million vehicles are recollected by Toyota because of faulty accelerator pedals that may cause runaway acceleration and faulty software that may cause braking to be delayed (wikipedia, n.d.).

(iii) *Commercial returns:* In this return type, products return from the buyer to the original sender against refunding. Generally, this type of return exists between any stages in a supply chain that have direct business contact. Based on some commitments, the buyer has a right to send back the product within a certain period. With this return type, transfer of financial risks from the buyer to the seller also occurs. Moreover, returned products can be reused or resold on alternative markets since they are unused and not defective. Returns related to fashion clothes and cosmetics can be given as examples (Fleischmann, 2000).

(iv) *Warranty and service returns:* Used products can return for repairing activities or replacing a new one within the warranty period. Alternatively, customers' money back upon which the returned product needs recovery. Furthermore, customers can still benefit from the services such as maintenance or repair after the warranty period has expired. On the other hand, they have no longer replace their product with a new one (Brito and Dekker, 2002). Marketing and regulations are listed as the main drivers of this product return type. Returns of defective household appliances and rotable spares can be given as examples (Fleischmann, 2000).

*(v)* *End-of-use and end-of-life returns:* End-of-use returns mean that flows of products that are disposed of after completion of their usage phase (Fleischmann, 2000). This also remarks to leasing cases and returnable containers like bottles, or returns to second-hand markets (Brito and Dekkers, 2002). End-of-life denotes that the returned product is in the end of its useful life time. This 'useful life time' is explained by Brito and Dekkers (2002) for the returned products which are at the end of their economic or physical life. Electronic equipment remanufacturing, carpet recycling and tire retreading are the results and examples of end-of-use returns. Some reseachers use the term end-of-life alternatively to the end-of-use. But end-of-use represent wider perspective. Because, returned products that come to their end of use phase may not be at the end of their economic or functional life (Herold, 2004).

All of the above reverse flows are summarized and categorized under three main topics (manufacturing-distribution-customer) according to supply chain tiers where these product returns occurred (Figure 2.2). In the scope of this thesis, while developing the further mathematical models, only the end-of-use and end-of-life returns are taken into account for spent battery and end-of-life tire recovery cases.

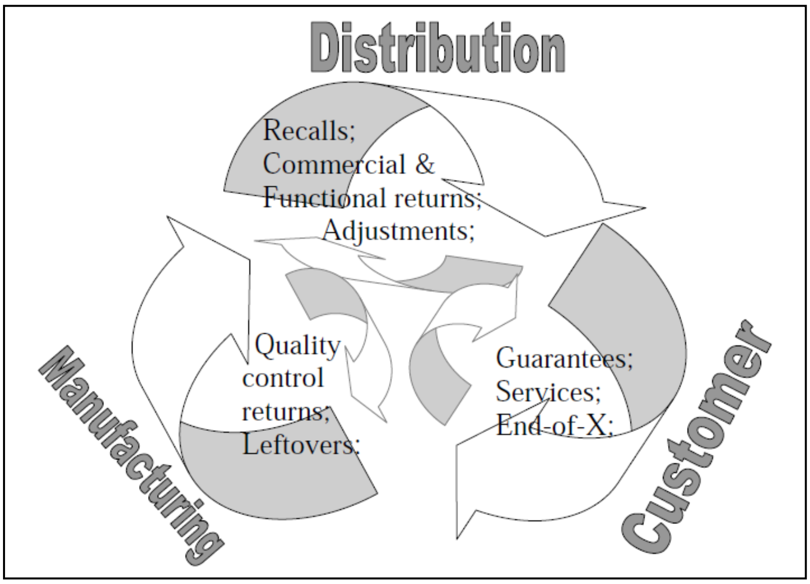



Figure 2.2 Schematic depiction of return reasons for RL (Brito and Dekker, 2002)

### 2.3 Basic Concepts in RL & CLSC Management

Three general options for returned products are resale, product recovery and disposition. For the product recovery option, main five alternatives are repairing, refurbishing, remanufacturing, cannibalization and recycling (Thierry, Salomon, Van Nunen, and Van Wassenhove, 1995). These basic RL activities or recovery options are displayed as can be seen in Figures 2.3, 2.4 and 2.5. The first one shows a basic RL network with its possible activities. Some of the other RL activities such as collection, inspection, sorting, disassembly and redistribution are also involved in the same figure. In addition to Figure 2.3, flows of both used and non-used products (packaging or waste) are shown on the RL activities diagram in Figure 2.4. On the other hand, depiction of an integrated supply chain where the all recovery alternatives are included is presented in Figure 2.5. This integrated network is extended by Brito and Dekker (2002) by adding various reverse flows and corresponding recovery options occurring in different supply chain tiers as given in Figure 2.6.

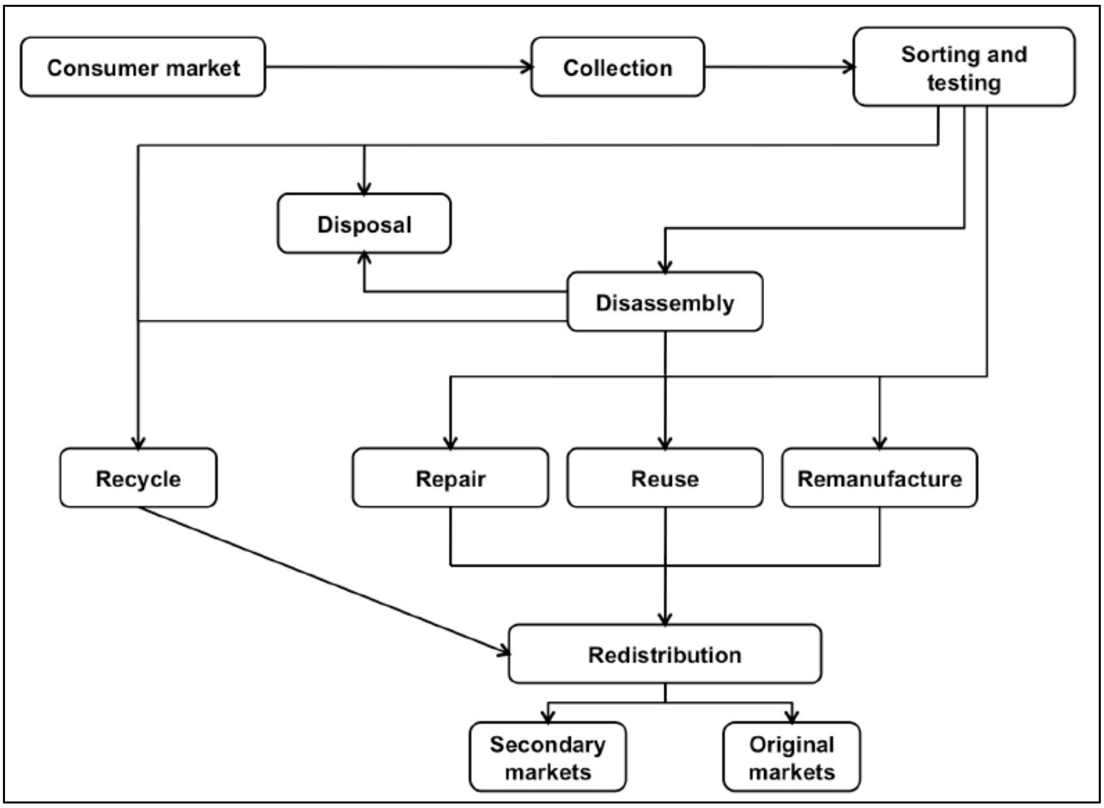



Figure 2.3 A RL network considering all possible activities (Paquette, 2009)

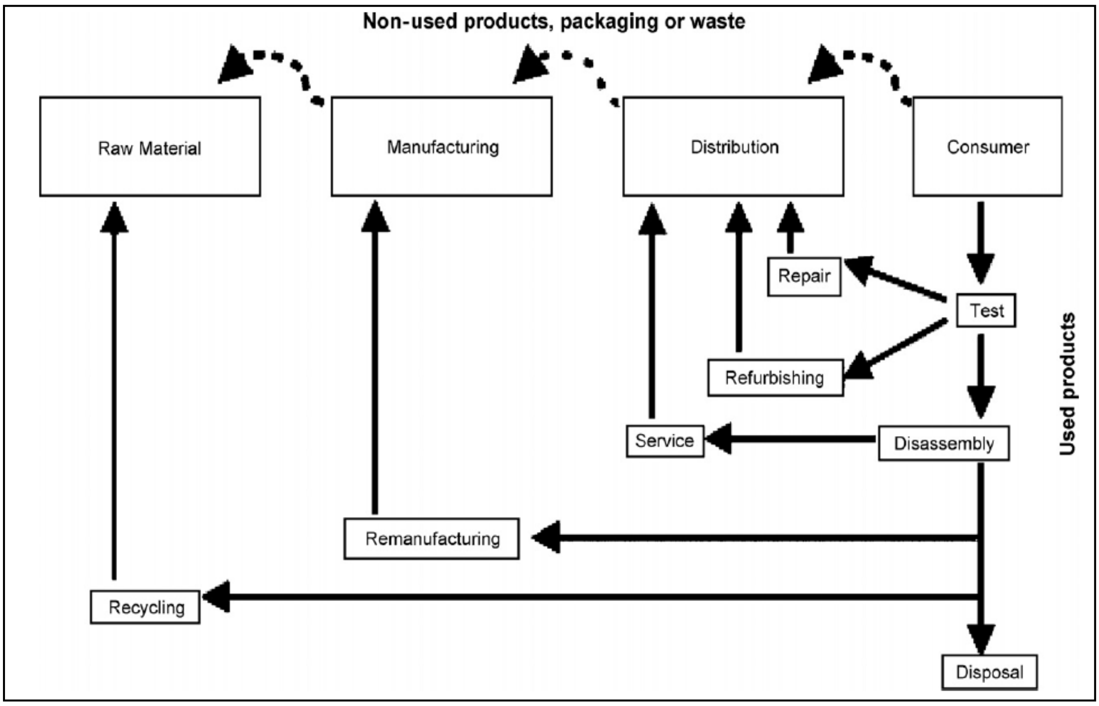
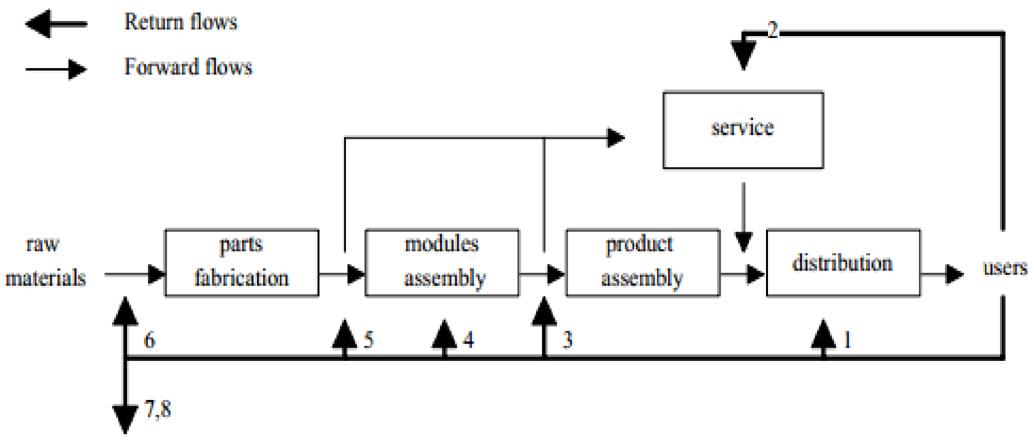



Figure 2.4 Flow diagram for alternative recovery options (Srivastava, 2008)

Complexity of these recovery operations and recovered value will increase from the bottom left to top right in Figure 2.4, (Brito and Dekker, 2002, 2003; Srivastava, 2008).




| Waste Management | 1. Product Recovery Management | | Direct Reuse |
|---|---|---|---|
| 7. Incineration<br>8. Landfilling | 5. Cannibalization<br>6. Recycling | 2. Repair<br>3. Refurbishing<br>4. Remanufacturing | 1. Direct reuse/ resale |

Figure 2.5 Integrated supply chain network including all of the recovery options (Quesada, 2003; Thierry et al., 1995)

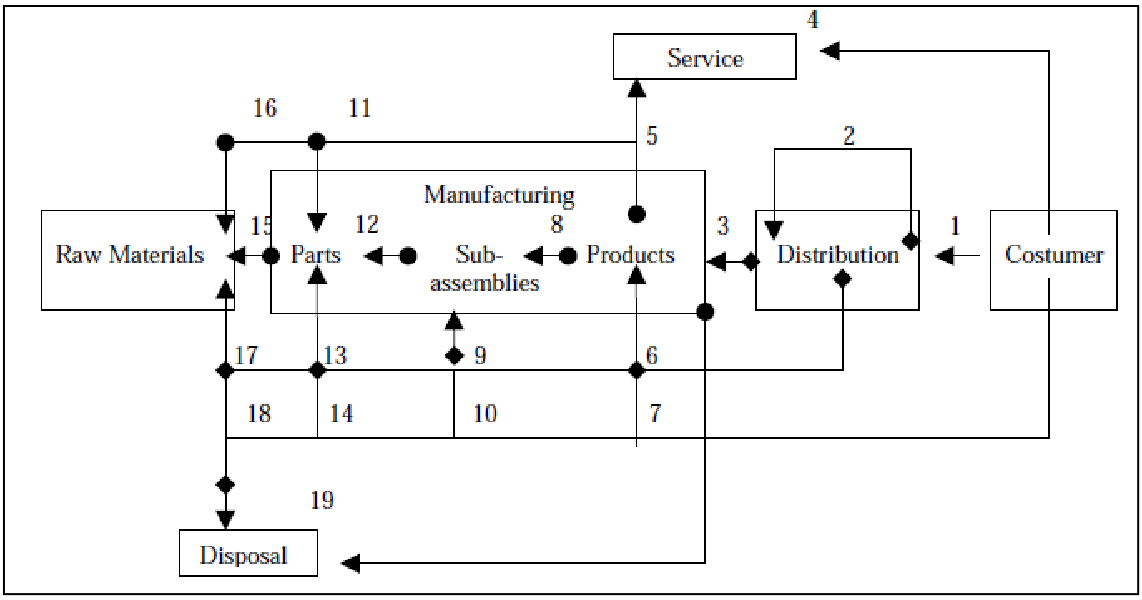



Figure 2.6 Extended version of the integrated supply chain network (Brito and Dekker, 2002)

Remarks corresponding to the numbers on Figure 2.6 are listed below (Brito and Dekker, 2002, 2003):

1. Reimbursement, End-of-use (Re-sale, Re-use)
2. Commercial & Stock adjustments (Re-distribution)
3. Recalls (Re-processing )
4. Warranty, Service (Repair)
5. Faulty Products (Repair)
6. Commercial returns, Recalls (Refurbishing)
7. End-of-Use, Warranty (Refurbishing)
8. Faulty products (Remanufacturing)
9. Commercial returns, Recalls (Remanufacturing)
10. End-of-Use, End-of-Life (Remanufacturing)
11. Faulty products (Retrieval)
12. Idem
13. Commercial Returns, Recalls (Retrieval)
14. End-of-life, End-of-Use (Retrieval)
15. Raw materials surplus ( Re-use, Re-sale)
16. Faulty Products, Production Leftovers (Recycling)
17. Commercial Returns, Recalls (Recycling)
18. End-of-Life (Recycling)
19. All Reverse Flow Types (Incineration, Landfilling)

Detail explanations related to these different recovery options are given in ongoing subsections.

### *2.3.1 Direct Reuse/Resale*

In the case of satisfying the quality requirements sufficiently, direct reuse or resale is an appropriate option for used products (Jayaraman, 2006). Only small changes or reprocessing activities such as cleaning and inspection are necessary for reusable items (Fleischmann et al., 2001; Karabulut, 2009). In this RL activity, physical and quality properties of products are unchangeable (Imre, 2006). Containers, bottles, pallets, packaging items, rechargeable batteries, carrier bags and twist ties, envelopes, jars and pots, old clothes, newspaper, scrap paper and tires can be given as examples for reusable items (recycling-guide, n.d.).

### *2.3.2 Repair*

The main aim of repairing option is returning the used products to working order. However, repaired products have less quality characteristics than the new ones. Generally, this option involves fixing and replacement of failed components. Therefore, other parts and modules are not affected by the repairing operations. These operations are usually conducted at the customer's location or repair centers (Jayaraman, 2006; Thierry et al., 1995). Limited disassembly and reassembly activities may be required during the repairing process (Karaçay, 2005). Automobiles, hydraulic pumps, navigational computers in aircraft, helicopter gearboxes, transportation equipment such as subway cars and buses, and high cost electronics are typical examples of repairable items (Jung, Sun, Kim, and Ahn, 2003).

### *2.3.3 Refurbishing*

The primary objective of refurbishing is bringing the used products up to specified quality levels or standards. But, these quality levels are less strict compared to the new products. In this recovery option, the modules which have critic or improper condition are first controlled then fixed or replaced with working or technologically superior ones. In other words, technology upgrading may be necessary for these outdated parts or modules. With these refurbishing operations, quality improvements can be provided and service life can be extended (Thierry et al., 1995). In addition, refurbishment option may be required for expensive products such as military and commercial aircrafts, computers, electronics and furniture etc.

### *2.3.4 Remanufacturing*

Remanufacturing can be defined as “the process of performing the required disassembly, sorting, refurbishing and assembly operations in order to bring parts of an end-of-life product (or the entire product) to a desired level of quality”. Furthermore, remanufacturing option preserves the product's (or the part's) identity (Gungor and Gupta, 1999). In this option, returned used products are disassembled all over and all of the modules and components are extensively controlled. Then, worn-out or outdated components and modules are replaced with new ones (Thierry et al., 1995). It is waited as good quality as a new product from the remanufactured products. It can be say that remanufacturing option covers refurbishing operations since all modules and parts are elaborately inspected before use process (Imre, 2006). Returned products merged the reverse supply chain at the fabrication level where it would be disassembled, remanufactured and reassembled to flow back by the retailers or dealers back to the customer as a remanufactured product (Jayaraman, 2006). During the remanufacturing operations, any product development activities can be performed. There are also suggestions from Ishii, Lee, and Eubanks (1995) and Gungor and Gupta (1999) for using reusable parts and packaging in design for remanufacturing. Useful explanation for providing clarification between the means of recycling and remanufacturing can be stated as “remanufacturing corresponds to product recovery while recycling means material recovery in the literature” (Gungor and Gupta, 1999).

The Remanufacturing Institute (TRI) explained the required circumstances for a product that can be considered for remanufacturing as follows (TRI, n.d.):

- Primary components should come from a used product.
- The used product is dismantled to the extent necessary to determine the condition of its components.
- The used product's components are completely inspected and cleaned for making free from rust and corrosion.

- All missing, defective, broken or substantially worn parts are either restored or they are replaced with new.
- Machining, rewinding, refinishing or other operations may be required for putting the product in sound working condition.
- The product is reassembled and controlled in terms of operating like a similar new product.

Motor vehicle parts, photo copiers, robots, office furniture, laser toner cartridges, aircraft parts, compressors, data communication equipment, bakery equipment, electrical apparatus, gaming machines, vending machines and musical instruments can also be given as products that are being remanufactured (TRI, n.d.).

### *2.3.5 Cannibalization*

All of the options mentioned earlier involve the usage of large part of the returned products. However, only a small portion of the returned product is being reused in cannibalization. In other words, recovering a limited set of reusable parts from the returned products and components is the main purpose of this option (Thierry et al., 1995). West Virginia Legislature (WVL) defined cannibalization as “removing parts from one commodity to use in the creation or repair of another commodity” (WVL, n.d.). Removed parts may be used in repairing, refurbishing and remanufacturing of other products or modules.

### *2.3.6 Recycling*

The main purpose of recycling option is expressed by Gungor and Gupta (2001) as “recovering the material content of retired products by performing required disassembly, sorting and chemical operations”. While performing these operations, identities of parts of end-of-life products are lost. In other words, functionality of the product is lost. In this option, returned products probably merge the reverse supply chain in the raw material procurement stage where they can be reused with other virgin raw materials to manufacture new products in case of appropriate condition of recovered materials (Jayaraman, 2006).

According to Natural Resources Defence Council (NRDC), main reasons of recycling can be summarized as follows (NRDC, n.d.):

1. Trees are saved by recycling.
2. Wildlife habitat and biodiversity protection can be provided.
3. Reduction of used toxic chemicals can be yielded by recycling.
4. Recycling helps curb global warming.
5. Water pollution can be reduced.
6. Recycling reduces the need for landfills.
7. Requirements for incinerators can be decreased.
8. In terms of social and economic issues, recycling creates jobs and promotes economic development.

Paper, steel, plastic, aluminium cans, glass, lead, copper, tire, water, rubber, computer, concrete etc. are examples for recyclable materials. In the scope of this thesis, remanufacturing, energy recovery and recycling are utilized as recovery options as well as product disposal alternatives in the developed mathematical models.

## 2.4 Other Issues

The remainder part of this Chapter gives general descriptions of most commonly encountered issues in product recovery literature such as environmental conscious manufacturing, green logistics and sustainable supply chains etc.

### *2.4.1 Product Recovery*

Main purpose of Product Recovery (PR) is minimization of the amount of waste sent to landfills by recapturing the materials and parts from used products through the aforementioned RL activities especially recycling and remanufacturing. Three main reasons of PR are listed by Gungor and Gupta (1999) as: (i) hidden economic value of solid waste, (ii) market requirements and (iii) governmental regulations. PR can be categorized into two parts namely, material recovery and product recovery. Material recovery generally includes disassembly operations and processing of parts/materials of returned products. The main aims of material recovery are minimization of the amount of disposal and maximization of the amount of the materials recovered and used in production phase. Main PR activities can be arranged as disassembly, cleaning, sorting, replacing or repairing bad components, reconditioning, testing, reassembling and inspecting. The recovered materials and products may be reused in repairing or remanufacturing of other products and components (Gungor and Gupta, 1999).

Ozdemir (2010) defined PR systems as “the combination of collection of used products from the end-consumers, inspection, sorting and selection of them, implementation of the most appropriate recovery strategy (e.g. repair, refurbish, remanufacturing, and recycling), disposal of non-recoverable waste materials/parts and redistribution of the remanufactured products to the appropriate markets” (p. 113). Factors for motivating the companies for PR are also listed by Ozdemir (2010) as: (1) growth in environmental consciousness of society and pressures of stakeholders on manufacturers, (2) lots of environmental regulations and legislation, (3) environmental problems and rapid depletion of landfills, (4) economic advantage obtained from metarial and product recovery, and (5) social responsibilities and targets of the firms.

Reductions in requirements of virgin material, energy consumption, environmental pollution are the main advantages of PR systems (Nnorom and Osibanjo, 2010). PR also can lead to profitable business opportunities and sustainable development. Three main roles of PR can be explained as follows:

(i) PR provides environmental and economic cost reduction in waste disposal,

(ii) purchasing and processing costs of the virgin materials can be decreased due to reuse components from used products,

(iii) PR can be seen as an effective marketing tool by firms for differentiating their products and services in an environmental aspect.

### *2.4.2 Environmental Conscious Manufacturing*

Darnall, Nehman, Priest, and Sarkis (1994) defined Environmental Conscious Manufacturing (ECM) as "the transformation of materials into useful products through a value-added process that simultaneously enhances economic well-being and sustains environmental quality" (p. 49). Main objectives of ECM are minimization of waste generated by production phase (mainly comes from the material and energy consumption) and prevention of the pollution. Structure of ECM can be divided into two major categories: design and analysis and management as depicted in Figure 2.7.

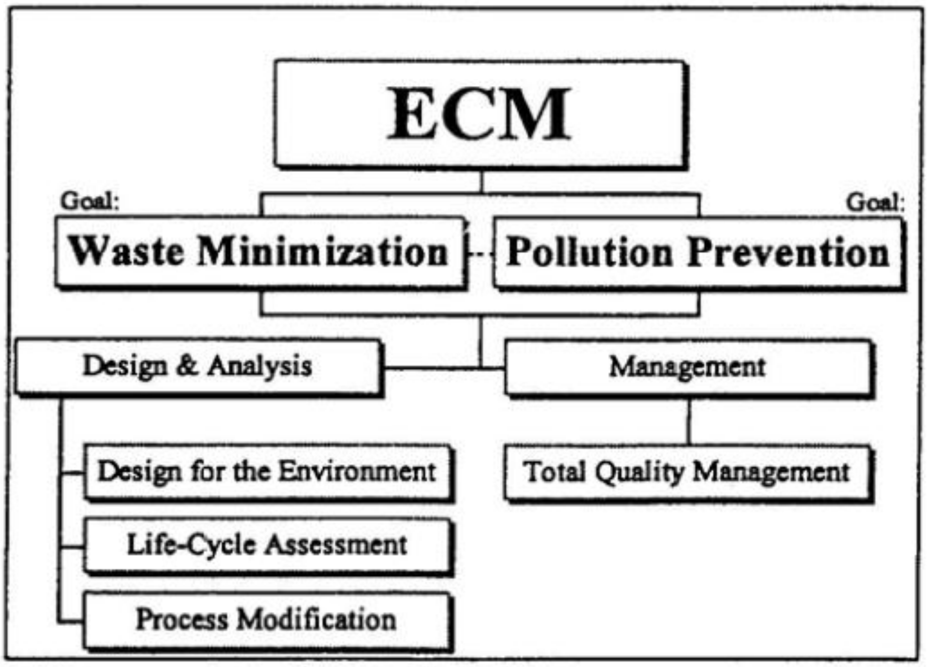



Figure 2.7 The ECM framework (Darnall et al., 1994)

Ilgin and Gupta (2010) emphasized that ECM pays attention to green principles which are concerned with developing methods for manufacturing products from conceptual design to distribution to consumers, and ultimately to the disposal, that meet environmental standards and requirements.

Furthermore, ECM is explained as a proactive approach by Zhang, Kuo, Lu, and Huang (1997) to minimize the product's environmental impact during its design and manufacturing phase for increasing the product's competitiveness in the environmentally conscious markets. Main benefits of ECM contain safer and cleaner factories, worker protection, reduced future costs for disposal, reduced environmental and health risks, improved product quality at lower cost, better public image and higher productivity.

Ultimately, another major objective of ECM is implied by Sarkis and Rasheed (1995) as “designing products that are recyclable or can be remanufactured or reused”. Thus, three elements of ECM are: reduce, remanufacture and reuse-recycle. These three strategies can lead to in decreasing of non-replenishable resources consumption and lower levels of pollution (Sarkis and Rasheed, 1995).

### *2.4.3 Green Logistics and Supply Chains*

All of the activities related to the eco-efficient management of both forward and reverse flows of goods and information are included in Green Logistics (GL) concept with the aim of meeting customer demand (Thiell, Zuluaga, Montanez, and Hoof, 2011).

GL deals with producing and distributing products in a sustainable way while considering environmental and social factors. Therefore, not only achieving the economic targets is taken into account but also wider effects on society, such as the effects of pollution on the environment are considered. This is the results of increasing interest in GL from firms and governments (Sbihi and Eglese, 2007).

Main GL activities can be ordered as redesigning packaging to use less material, reducing the energy and pollution from transportation. Moreover, most of the RL activities are lying within GL area (Zuluaga and Louranco, 2002).

Hervani, Helms, and Sarkis (2005) defined Green Supply Chain Management (GSCM) as demonstrated in Eq. (2.1) and also gave the graphical abstract of this equation as in Figure 2.8.

$$GSCM = Green\ purchasing + Green\ manufacturing \left( \begin{matrix} Materials \\ management \end{matrix} \right) + Green\ distribution\ (Marketing) + Reverse\ Logistics \quad (2.1)$$

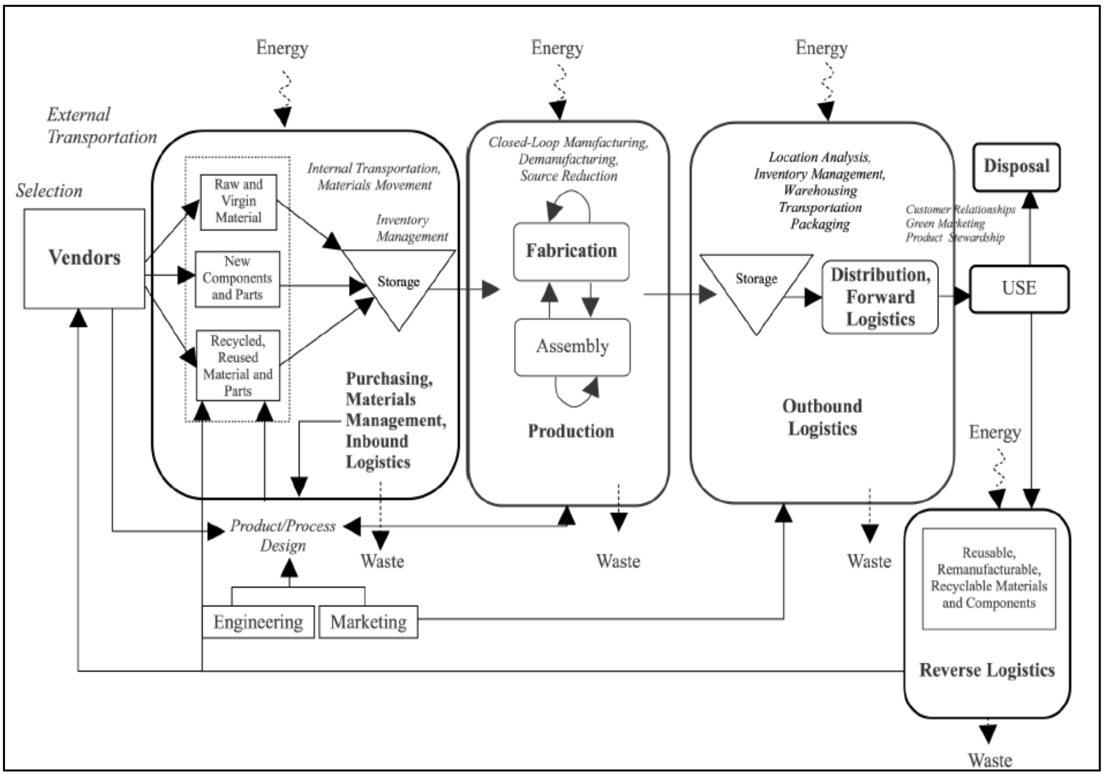



Figure 2.8 Graphical description of GSCM (Hervani et al., 2005)

GSCM is a key issue for strengthening companies' competitiveness, increasing enterprise economic benefits, decreasing environmental pollution and improving the efficiency of resource utilization. In contrast to traditional supply chain, GSCM concerns environmental protection, resource conservation and maximal economic gain (Ying and Li-jun, 2012).

### *2.4.4 Sustainable Logistics and Supply Chains*

Economic, environmental and social objectives should be satisfied simultaneously as a requirement of sustainable development for achieving the following goals (Dehghanian and Mansour, 2009):

- Maintain a high and stable level of economical growth and employment.
- Effective protection of the environment.
- Provide social progress which recognizes the needs of every one.

In other words, there are three pre-requisites of sustainable development: resource conservation, environmental protection and social development (Amin and Zhang, 2012). Besides them, Sustainable Logistics (SL) concerns with reducing environmental and other negative impacts of all logistics activities, mainly transportation/distribution. Sustainability aims to ensure that decisions made today do not have an unfavorable impact on future generations.

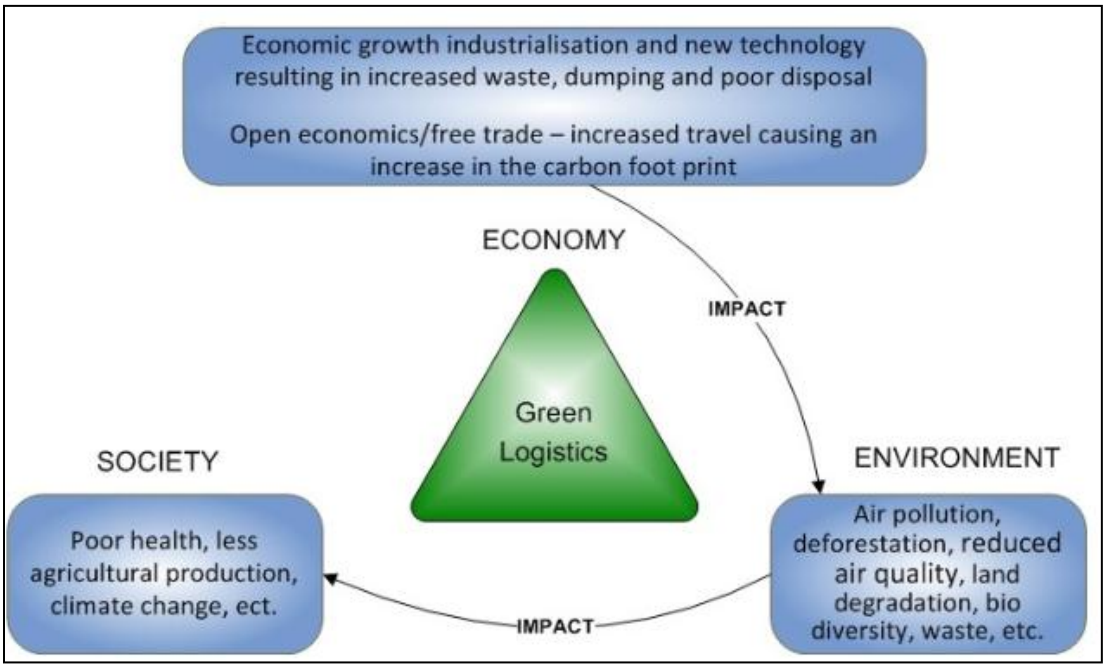



Figure 2.9 Main components of sustainable logistics and supply chains (Logistics Cluster, n.d.)

Sustainable Supply Chain (SSC) is defined by Seuring and Müller (2008) 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” (p. 1700). In SSCs, environmental and social criteria need to be satisfied by supply chain members to stay within the supply chain. However, competitiveness would be provided by meeting customer needs and related economic criteria (Seuring and Müller, 2008).

Most common business drivers of supply chain sustainability are depicted in Figure 2.10. In order to determine these drivers for a specific company, variety of issues should be taken into account such as including industry sector, supply chain footprint, stakeholder expectations, business strategy and organizational culture (The Golabal Compact [TGC], 2010).

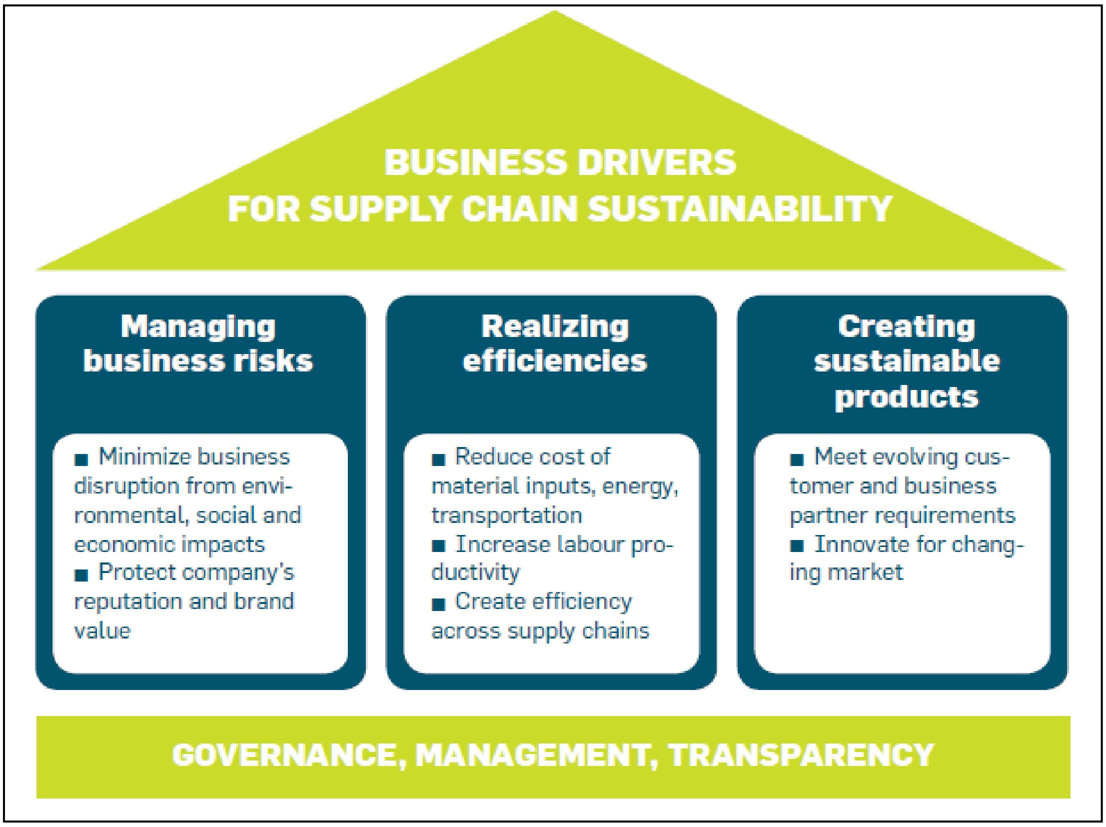



Figure 2.10 Specific business drivers for supply chain sustainability (TGC, 2010)

# CHAPTER THREE
# LITERATURE REVIEW ON REVERSE LOGISTICS & CLOSED-LOOP SUPPLY CHAIN NETWORK DESIGN

## 3.1 Introduction

In this Chapter, literature survey is distinguished in three main topics: (i) solution approaches to RL & CLSC network design problems such as mixed integer programming, decomposition methods and heuristic based methodologies, (ii) modelling approaches for uncertainty such as stochastic, possibilistic etc. and finally (iii) selective overview of main modelling features in RL & CLSC network design. In addition to this Chapter, each further Chapter includes its own specific literature survey. For instance, multi-objective RL & CLSC network models and application of fuzzy goal programming with different importance and priorities (FGP-DIP) are reviewed in Chapter 4. Additionally, other fuzzy goal programming (FGP) techniques such as weighted additive method, interactive FGP etc. which are used in RL & CLSC network design are discussed. In Chapter 5, applications of eco-indicator 99 method in supply chain design and planning are reviewed. Furthermore, literature review on tactical planning problems in CLSCs is also given in Chapter 6.

RL & CLSC network design problem aims to determine locations of facility such as distribution, collection and recovery centers; capacity levels for processes, allocate production/recovery of products to the facilities as well as optimize product flows between these facilities at the various locations. Major classifications related to the RL & CLSC management are made by Salema, Barbosa-Povoa, and Novais (2007) and Ilgin and Gupta (2010). This research area can be divided into three important topics namely distribution, production planning and inventory when looked from the perspective of operations research (Salema, Barbosa-Povoa, and Novais, 2007). In terms of RL and CLSC network design, this problem type is divided into two groups as deterministic and stochastic and evaluated by Ilgin and Gupta (2010) under the topic of Reverse & CLSCs in the literature of environmentally conscious manufacturing and product recovery.

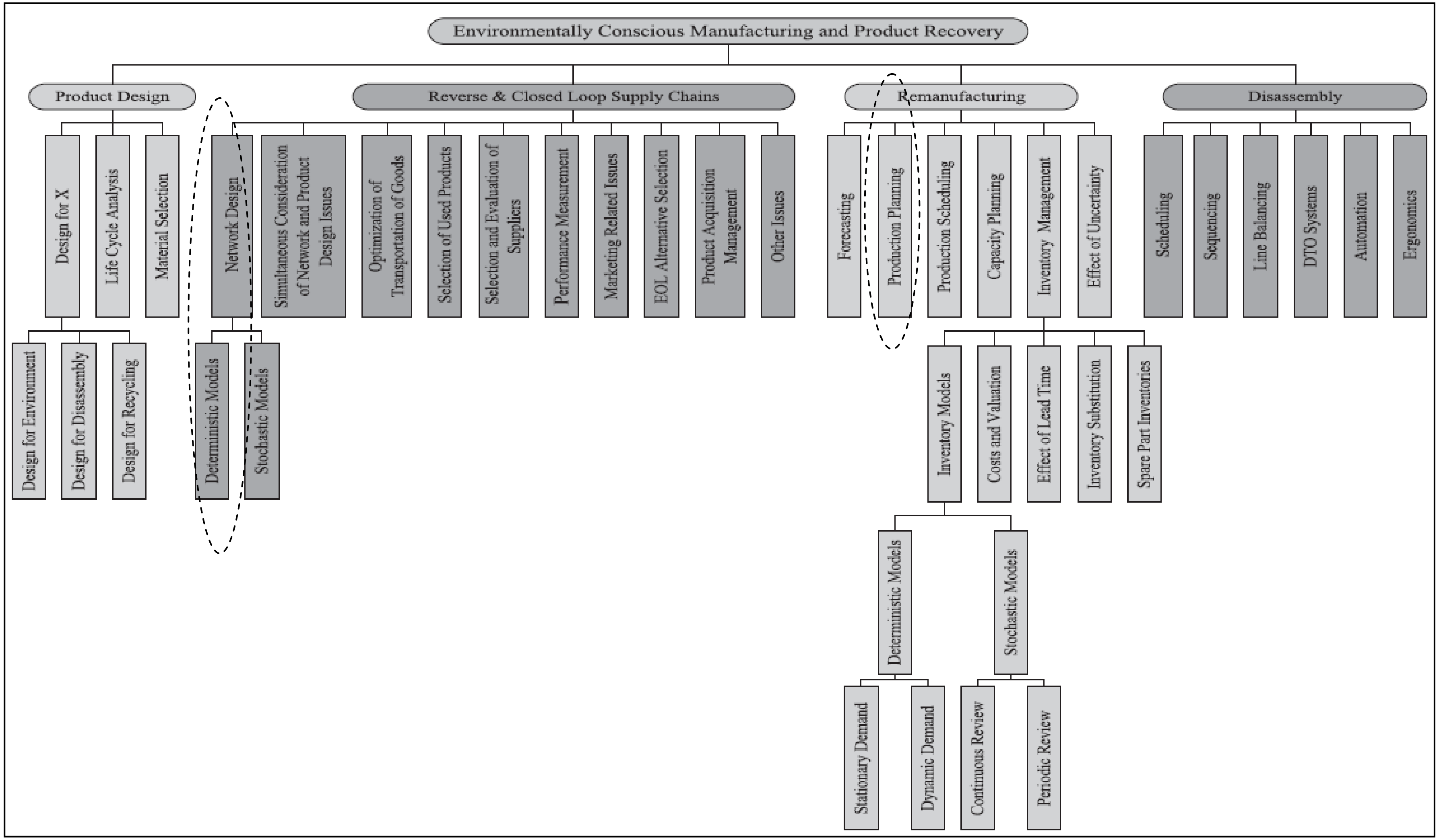



Figure 3.1 A comprehensive literature classification related to ECM and product recovery (Ilgin and Gupta, 2010)

They emphasized that the most of the related deterministic studies take into account the only reverse flows with the modelling technique of mixed integer programming. However, in stochastic RL network design models, uncertainty regarding with timing, quality and quantity of product returns is tried to handle using robust optimization technique.

In the scope of this thesis, we concern the topics which are shown in Figure 3.1 with dashed circles: strategic planning (network design problem for RL & CLSCs) and tactical planning (production planning with remanufacturing option) by using mixed integer programming technique in crisp and fuzzy environments.

### 3.2 Different Solution Approaches to RL & CLSC Network Design Problem

Fleischmann (2001) proposed the most generic recovery network model in order to determine the number of facilities, their locations and quantities of both forward and reverse goods flows while considering three intermediate levels of facilities: plants, distribution warehouses and disassembly centers, then used mixed integer linear programming optimization technique.

This generic recovery network model was extended by Sim et al. (2004) by adding more realistic conditions such as planning period and various transportation modes. Because, time phased-planning is crucial since the irreversible property of the structural decisions in designing the network. Also, not all of the transportation modes can be used in each time period or related transportation costs may change throughout the planning horizon.

Salema et al. (2007) reformulated this generic model while taking into account the production/storage capacities of opened facilities, multiple product production and uncertainty related to the amounts of customers' demand and product returns by employing multiple-scenario based approach. Since the major problem in product recovery network models is uncertainty related to demand and return quantities, they employed multi-scenario approach which uses associated probability value for each scenario and related demand and return amounts which have uniform distribution. According to their results, capacity limitations have a significant impact on the design of the optimal network. However, using scenario based approach results increase in problem size and CPU time for solving the problem. For this reason, application of decomposition methods such as Benders decomposition is suggested by the authors.

A bi-level optimization model for simultaneous location-allocation of facilities was developed by Srivastava (2008) in RL environment. All input parameters, variables and constraints regarding product returns are derived from the informal interviews. In the first stage of the proposed hierarchical optimization model, locations of the collection centers and related product returns are provided from the solution of simple optimization model coded in GAMS with the objective of minimizing investment costs and the strategic, customer convenience constraints. Then detailed RL network design including disposition decisions, location and capacity addition decisions for rework sites is obtained from the main model which tries to maximize profit.

A mixed integer linear programming model was developed by Demirel and Gokcen (2008) for a multi-echelon, multi-product deterministic CLSC network design considering remanufacturing option in order to locate disassembly, collection and distribution facilities. They validated their model by performing numerical experiments with different scenarios (low, medium and high return rates) for each problem size. According to their experimental results, time to find the optimal solution and total cost of the system generally increase in the case of large scale problems. In addition, based on the increases in return rates, cost reduction can be saved for the remanufacturing system.

Sasikumar, Kannan, and Haq (2010) formulated a mixed integer non-linear programming model for maximizing the overall profit of a multi-echelon, multi-period RL network with a real life case of truck tire remanufacturing. They added the sales of retreaded tires to the secondary markets with %30 to %50 discounts to their model since the lack of serving remanufactured products to secondary markets in the literature. At the end of that study, they investigated the sensitivity of the proximity of initial collection centres to the customer locations in order to find the maximum allowable distance between them. Because, opening of larger number of initial collection centres may be required in the case of reducing the maximum allowable distance. Thus, this study tried to compromise total RL costs and customer service level.

Subulan and Tasan (2011b) extended the previously mentioned RL network design model for end-of-life tires by integrating the forward flows and considering different recovery options simultaneously such as remanufacturing, recycling and energy recovery for a more holistic multi-period CLSC network design problem.

Configuration of a CLSC network based on the product life cycle is provided by Amin and Zhang (2012) via mixed integer linear programming technique with the objective of profit maximization. In detail, three return/recovery pairs namely commercial, end-of-use and end-of-life are taken into account in the design phase. In their extended model, selling of remanufactured products to the secondary markets is handled and sensitivity analysis are also conducted for both general and extended model in order to investigate changes of objective function by varying capacities and maximum percent of each return type. Uncertainty of some parameters such as demand and returns are suggested to be considered with multiple time periods for the future works.

Another deterministic mathematical model that considers three recovery options: disassembly, recycling and repairing is proposed by Dat, Trunch Linh, Chou, and Yu (2012) for RL network design of waste electrical and electronic products so that minimize the total RL costs composed of collection, fixed investment, disposal, treatment and transportation as well as considering revenue obtained from the sales of returned products and renewable materials. The purpose of their study is deciding the optimal facility locations and material flows in the RL network. They took into account aforementioned three recovery options: disassembly, recycling, repairing and disposal since each type of waste product tracks different recycling processes based on its characteristic. The proposed model is illustrated by a numerical example which involves computers, televisions and cell phones as returned product types. According to the results, transportation costs constituted the large amounts of the total cost structure and can be reduced by different ways such as consolidation etc.

Das and Chowdhurry (2012) developed a mixed integer linear programming model for a CLSC planning with modular design architecture and different quality levels of sold products to the markets with the objective of overall profit maximization. They tried to determine: (i) amounts of recovered modules at recovery service providers, (ii) optimal product mixture at different quality levels, (iii) production quantity of new modules at plants, (iv) purchasing quantities of new components from the suppliers, (v) transportation-distribution amounts to the retailers by considering collection of returnables through these retailers. At the end of that study, sensitivity analysis are conducted in order to investigate the influence of changes in demands for recovered products with different quality levels on revenue, total cost and profit/cost ratio.

Due to the undesired long computational time and bad solution quality of large scale or real life RL & CLSC network design problems, some researchers used heuristic based approaches or decomposition methods as a solution methodology. For instance, an efficient dual problem solution method based on Benders decomposition with multiple Benders cuts was proposed by Uster et al. (2007) to solve a mixed integer linear programming model for a real life CLSC network of an OEM in the automotive industry. They seek to determine the locations of potential collection centers and remanufacturing facilities also integrate the forward and reverse flows in the CLSC. In the solution phase of the problem, they proposed an efficient dual problem solution method (exact solution methodology) based on Benders decomposition with multiple Benders cuts. In contrast to the conventional single Benders cut approach, proposed solution method with multiple Benders cuts yields stronger lower bounds and faster convergence to optimality than the branch-and-cut approach and single Benders cut approach.

Since the RL network design pertains to a class of NP-complete problem (Schrijver, 2003), Min, Ko, and Ko (2006) used genetic algorithm to solve the proposed mixed integer non-linear programming model for a RL network design which aims to locate initial collection points and centralized return centers.

A priority based genetic algorithm was proposed by Lee, Gen, and Rhee (2009) for a multi-product, three stage RL network design problem with the objective of minimizing the total cost which consists of shipping costs and fixed opening costs of disassembly centres and processing centres. Their encoding method is composed of combined a new crossover operator namely weight mapping crossover for the first and second stages of the problem. Also, a heuristic approach is implemented in the third stage. A numerical experiment is performed for showing the performance of the priority based genetic algorithm with weight mapping crossover in terms of solution quality.

Extended version of the generic recovery model was solved by Sim et al. (2004) by using LP based genetic algorithm which uses LP based solution and genetic operators. They obtained better solutions than traditional genetic algorithm in terms of solution quality (cost) and superior solutions than CPLEX in terms of time.

A genetic algorithm based heuristic was proposed by Kannan, Sasikumar, and Devika (2010) for solving the developed multi-echelon, multi-product and multi period CLSC network design model for a battery recycling case. Their model provides decisions about material procurement, production, distribution, recycling and disposal. Results showed that the used methodology provides better outcomes in terms of quality of solutions and computational time for the larger scale problems which could not obtained any feasible solution for these problems by GAMS or other commercial software.

All of the previously mentioned studies are summarized as seen in Tables 3.1 and 3.2, and regarding important notes are also added.

Table 3.1 Single objective RL & CLSC network design models via mixed integer programming

| Article | Note |
|---|---|
| Fleischmann (2001) | "Generic recovery network model" |
| Sim, Jung, Kim, and Park (2004) | "Generic model with planning periods and transportation modes" |
| Salema, Barbosa-Povoa, and Novais (2007) | "Generic model with production/storage capacities, multiple product production, uncertain demand and product returns" |
| Srivastava (2008) | "Bi-level hierarchical optimization model" |
| Demirel and Gokcen (2008) | "RL network design with remanufacturing option" |
| Sasikumar, Kannan, and Haq (2010) | "A non-linear model for multi-period RL network design of truck tire remanufacturing" |
| Subulan and Tasan (2011b) | "CLSC network design considering multiple recovery options for end-of-life tires" |
| Amin and Zhang (2012) | "CLSC configuration based on product life cycle" |
| Dat, Truch Linh, Chou, and Yu (2012) | "RL network design of waste electrical and electronic products" |
| Das and Chowdhurry (2012) | "CLSC planning with modular design architecture" |

Table 3.2 RL & CLSC network design with decomposition and heuristic based solution methodology

| Article | Note |
|---|---|
| Uster, Easwaran, Akcali, and Cetinkaya (2007) | "Dual problem solution method based on Benders decomposition" |
| Lee, Gen, and Rhee (2009) | "A priority based genetic algorithm for RL network design" |
| Sim, Jung, Kim, and Park (2004) | "LP based genetic algorithm for generic recovery network model" |
| Kannan, Sasikumar, and Devika (2010) | "Genetic algorithm based heuristic for a battery CLSC network design" |

## 3.3 RL & CLSC Network Design under Uncertainty

Uncertainty in timing, quality and quantity of product returns is an important problem in RL & CLSC network design. As mentioned by Ilgin and Gupta (2010), this issue can be handled by using robust optimization technique in stochastic RL network design models.

A two-stage stochastic programming model was proposed by Kara and Onut (2010) for single product, two-echelon capacitated RL network design in waste paper recycling industry in order to maximize revenue. Locating collection centres and recycling centers and allocating flow amounts between the nodes efficiently were the main aims of that study. Demand and amounts of collected products are assumed to be uncertain and fitted to the normal distribution while generating alternative scenarios. For providing the relevant data such as possible location alternatives, a comprehensive questionnaire is conducted. Also, face to face interviews are held. Location and allocation decisions are assigned in sequence in the first and second stages of the stochastic programming model. Consequently, it is proved that their stochastic model yields more economical and compromised solutions for the recycling network design.

Lee, Dong and Bian (2010) also proposed a two-stage stochastic programming model for sustainable logistics network design. In their model, they planned opening potential forward facilities, collection facilities and hybrid facilities which provide benefits of cost savings and pollution reduction due to the common usage of material. Demands of forward products and the supply of returned products are assumed to be stochastic parameters which have known distribution. Sample average approximation scheme that is based on crude Monte Carlo samples and importance sampling strategy are integrated as the solution approach for increasing the efficiency and decreasing the variance of the solution. At the end of the study, sensitivity analysis of return ratio is also carried out by using both sequential method and the proposed integrated method for analyzing the influence of this ratio. Results indicated that integrated method yields a network with lower costs.

Because of the some disadvantages of the stochastic programming such as difficulty related to availability of historical data and complex modelling, uncertain (dynamic) demand and purchasing cost in a strategic agile CLSC network design problem of perishable goods (food and high-tech industries) was handled via interval robust optimization technique by Hasani, Zegordi, and Nikbakhsh (2011). Because, these industries have common characteristics or time dependent properties such as perishable lifetime and perishable price. That study also considers the BOM based on reusing the returned products and disassembling the returned products in order to reuse their parts. That study also provides decisions ragarding supplier selection, production, transportation, purchasing and recovery planning in each period. All of the non-linear constraints which involve max and min terms are trasformed into the linear form. Solution of the deterministic and robust models are obtained by LINGO 8.0 commercial optimization solver. At the end of the study, total cost of the system in the presence of uncertainty is obtained greater than the deterministic condition due to the additional costs imposed on the system (increased cost of unsatisfied demand).

Uncertain demands, returns, delivery times, costs and capacities were taken into account using possibilistic programming approach by Pishvaee and Torabi (2010) in a CLSC network design which integrates strategic and tactical planning decisions. Because, most of the parameters in CLSC network design problem have imprecise nature or incomplete information. Objectives of their study were minimization of total cost that measures network efficiency and minimization of total tardiness which is related to the network responsiveness. For solving the model, a two-phased approach is proposed based on hybridization of methods developed by Jimenez, Arenas, Bilbao, and Rodriguez (2007); and Parra, Terol, Gladish, and Rodriguez Uria (2005) in order to convert the possibilistic model including the imprecise coefficients in both objective functions and constraints in to the crisp equivalent in the first phase. In the second phase, an iterative fuzzy solution approach is proposed by combining the new fuzzy multi-objective approaches developed by Torabi and Hassini (2008); Selim and Ozkarahan (2008). Results of these two methods were compared with each other on the test problems and came to the conclusion that efficient solutions can be provided by these two methods.

Uncertainties in demand and yield rate are modelled by Qiang, Ke, Anderson, and Dong (2012) for a CLSC network with decentralized decision makers that composed of raw material suppliers, retailers and manufacturers.

Summary of the above studies is also given in Table 3.3.

Table 3.3 RL & CLSC network design models under uncertainty

| Article | Note |
|---|---|
| Kara and Onut (2010) | "Two stage stochastic programming model for RL network design in waste paper recycling" (Demands and amounts of collected products are uncertain) |
| Lee, Dong, and Bian (2010) | "Two stage stochastic programming model for sustainable logistics network design" (Demands and supply of returned products are stochastic parameters) |
| Hasani, Zegordi, and Nikbakhsh (2011) | "Interval robust optimization technique for perishable goods" (Uncertain demand and purchasing cost) |
| Pishvaee and Torabi (2010) | "Possibilistic programming approach to CLSC network design" (Uncertain demand, delivery times, costs and capacities) |
| Qiang, Ke, Anderson, and Dong (2012) | "CLSC network design with decentralized decision makers" (Uncertain demand and yield rate) |

### 3.4 A Review of Main Modeling Characteristics in RL & CLSC Network Design

In this section, we compared our proposed Model II (in Chapter 5) with the current literature in terms of main modeling characteristics or features handled in the mathematical model development phase. We offered a selective overview of the most relevant papers in Table 3.4 based on the nine main features determined by Alumur, Nickel, Saldanha-da-Gama, and Verter (2012). Besides these nine features, we added six more modeling features namely; integration of forward and reverse flows (CLSC concept), multi-objectivity, vehicle type or transportation mode, technology selection regarding production, recycling and remanufacturing, environmental issues and uncertainty approaches which are required for more realistic RL and CLSC network design.

Table 3.4 Modeling characteristics of CLSC network design and relevant papers

| Article | Location decisions for both forward and reverse activities | | | | Integrated forward and reverse flows (CLSC) | Multiple objective | Reverse BOM | Vehicle type or Transp. mode | Dynamic returns | Dynamic location | Capacity | Minimum throughput | Technology selection | Environ. issues | Uncertainty (Fuzzy or stochastic approaches) | Secondary market and profit orientation |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Distribution centers/ plants | Centralized return points or collection | Retreading (Remanufacturing) | Recycling | | | | | | | | | | | | |
| Krikke et al. (2003) | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | | | | | | | ✓ | | |
| Sim et al. (2004) | ✓ | | ✓ | | ✓ | | ✓ | ✓ | ✓ | ✓ | C | | | | | |
| Realff et al. (2004) | ✓ | ✓ | ✓ | ✓ | | | ✓ | ✓ | ✓ | | C | | | | ✓ | ✓ |
| Lieckens& Vandaele (2007) | | | ✓ | ✓ | | | | | | | ML | | | | ✓ | ✓ |
| Min and Ko (2008) | ✓ | | ✓ | | ✓ | | | | ✓ | ✓ | C | | | | | |
| Salema et al. (2009) | ✓ | | ✓ | | ✓ | | | | ✓ | | C | ✓ | | | | ✓ |
| Dehghanian and Mansour (2009) | | | | ✓ | | ✓ | | | | | ML | | | ✓ | | |
| Fonseca et al. (2010) | | ✓ | | ✓ | | ✓ | ✓ | | | | M | | ✓ | | ✓ | |
| Kannan et al. (2010) | | | | | ✓ | | ✓ | | ✓ | | C | | | | | |
| Sasikumar et al. (2010) | | ✓ | | | | | | | ✓ | ✓ | C | | | | | ✓ |
| Pishavaee and Torabi (2010) | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | | | ✓ | | C | | | | ✓ | |
| Wang and Hsu (2010) | ✓ | | | ✓ | ✓ | | | | | | C | | | | | |
| Subulan and Tasan (2011b) | ✓ | ✓ | ✓ | | ✓ | | ✓ | | ✓ | | C | | | | | ✓ |
| Bouzembrak et al. (2011) | ✓ | | ✓ | | ✓ | ✓ | | ✓ | | | C | | ✓ | ✓ | | |
| Hasani et al. (2011) | ✓ | | | | ✓ | | ✓ | | ✓ | ✓ | C | | | | ✓ | ✓ |
| Gomes et al. (2011) | | ✓ | | ✓ | | | ✓ | ✓ | ✓ | | C | | | | | |
| Pishavaee and Razmi (2012) | ✓ | ✓ | | | ✓ | ✓ | | | | | C | | | ✓ | ✓ | |
| Ozceylan and Paksoy (2012) | ✓ | | | | ✓ | | ✓ | | ✓ | ✓ | C | | | | | |
| Chaabane et al. (2012) | ✓ | | | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | C | | ✓ | ✓ | | |
| Alumur et al. (2012) | | ✓ | ✓ | ✓ | | | ✓ | | ✓ | ✓ | M | ✓ | | | | ✓ |
| Proposed model | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | M | ✓ | ✓ | ✓ | ✓ | ✓ |

'C': Capacitated, 'M': Modular capacities, 'ML': Multi-level capacities

Thus in Chapter 5, we developed a multi-period CLSC network design for an end-of-life tire recovery system in order to overcome some drawbacks discussed by Alumur et al. (2012) and took the dynamic nature of the problem into account. With inclusion of these additional features to the proposed model, we present more holistic model and progress beyond the literature.

Furthermore, multiple recovery options and application of an environmental impact assessment method (Eco-indicator 99 method) have scarcely been addressed in sustainable CLSC network design concept. Therefore, Chapter 5 presents a novel mathematical model which includes wide range of modeling characteristics as mentioned above and separates from the other studies in literature with its holistic view.

# CHAPTER FOUR
# A FUZZY GOAL PROGRAMMING APPROACH TO STRATEGIC PLANNING PROBLEM OF A LEAD/ACID BATTERY CLOSED-LOOP SUPPLY CHAIN

## 4.1 Introduction

The increasing numbers of automobiles, trucks, motorcycles on roads as well as boats, marine crafts and several industrial applications have caused continuously increasing demand for lead/acid batteries. Nowadays, along with these demand increments and some difficulties encountered in Turkey, such as the lack of producing pure lead economically from the primary sources and prohibition on import of scrap batteries have made RL activities and battery recycling important issues in the lead/acid battery industry.

Furthermore, as a result of providing the large part of industrial lead requirements through imports with highly purchasing costs instead of producing pure lead from the primary sources, the battery manufacturers have been forced to obtain lead by using secondary sources and to build-up an effective and efficient spent battery collection and recovery systems.

Briefly, economical, environmental and governmental considerations have forced the lead/acid battery manufacturers to build-up an effective and efficient spent battery collection and recovery systems. In addition, according to Battery Council International (BCI), lead/acid battery recovery systems have an environmental success story; more than 97% of all battery lead can be recycled. This rate is quite high when compared to 55% of aluminium soft drink and beer cans, 45% of newspapers, 26% of glass bottles and 26% of tires. Also, the recyclable components of lead/acid batteries such as lead and plastics can be recycled so many times (BCI, n.d.). From the perspective of the health and environmental aspects, spent lead/acid batteries consist of lead, lead compounds and sulphuric acid, all of them are very toxic and hazardous. Therefore, scrap lead/acid batteries are classified as hazardous waste under the Hazardous Waste Act - 1989 and should not be disposed of in ordinary garbage. Lead is a cumulative poison in human's body and also harmful to the environment, particularly fish, animals and plants. The electrolyte in batteries is corrosive and can cause loss of eyesight and skin damages if the battery explodes. Moreover, the plastic parts such as polypropylene casing (box) is not biodegradable and it is appropriate for recycling. Therefore, spent batteries should be recycled into new ones made from the lead, sulphuric acid and polypropylene since using less energy than refining primary ore and removes lead from the environment (brighthub, n.d.; recyclingnearyou, n.d.).

Both these economical and environmental issues with the legal obligations have a pressure on battery manufacturers and all other stakeholders of lead/acid battery supply chain to manage the reverse flows of the used batteries. The design and implementation of an effective and efficient collection-recovery system are affected by the distribution, collection and recycling facilities' location decisions which are strategic and essential. Since the strategic planning problem is crucial for the lead/acid battery sector and the multi-objective reverse and CLSC network design models have been rarely discussed in the literature; this Chapter presents a multi-objective linear programming (MOLP) model with different importance and priorities for the network design problem of a lead/acid battery CLSC in fuzzy environment.

In the proposed model, both forward-reverse flows and their mutual interactions are considered simultaneously in an integrated model with the environmental and cost perspectives mentioned above. Uster et al. (2007) highlighted that RL networks which are independent of the forward flows will cause accretion in infrastructure costs and potential profit reduction related to the recovery option such as recycling, remanufacturing etc. Therefore, optimal network design requires the consideration of forward and reverse flows simultaneously.

The main purpose of this Chapter is to develop a multi-objective, multi-echelon and multi-product strategic planning model for the lead/acid battery CLSC. Fuzzy goal programming approach with different importance and priorities which was developed by Chen and Tsai (2001) is used to solve the proposed model.

In the proposed model, minimization of the total cost of CLSC which consists of fixed investment costs, production costs, transportation costs, material and purchasing costs regarding materials/components and spent batteries, recycling costs, collection costs and disposal cost; maximization of the collection of returned batteries covered by the opened collection centres and hybrid facilities; and finally maximization of the total volume flexibility that includes manufacturing-recycling and distribution-collection volume flexibility are addressed as the objective functions. In fact, flexibility is an important measure. Due to the nature of reverse flows, new flexibility objectives namely total recycling and collection volume flexibilities are added to the predefined objective function, total volume flexibility. Solution of the proposed model provides us the decisions related to distribution centres', collection centres', hybrid facilities' and licensed recycling facilities' physical locations and optimal values of production, collection, recycling, transportation and purchasing quantities of both used scrap batteries and materials/components.

## 4.2 Chapter Outline

This Chapter is organized as follows. The literature related to multi-objective optimization of RL & CLSC network design problems and applications of FGP-DIP are given in section 4.3. Details of the problem with the notation, model parameters, decision variables and mathematical model formulation are described in section 4.4. In section 4.5, the proposed model is applied to a case study inspired from lead/acid battery sector in Turkey for depicting the validity and practicality of the proposed model and efficient compromise solution of the proposed model with the satisfaction of multiple fuzzy goals is achieved by using ILOG OPL Studio version 6.3. Section 4.6 demonstrates the fuzzifing of the proposed strategic planning model and contains the construction of the membership functions, determination of the desirable achievement degrees for all fuzzy objectives by using linguistic variables and transformation of the fuzzy model to the equivalent crisp mathematical formulation. Sensitivity analysis of the proposed model is also presented considering different scenarios in section 4.7. Finally in section 4.8, Chapter conclusion and future works are given.

### 4.3 Literature Review on Multiple Objective RL & CLSC Network Design and Applications of FGP-DIP

In this section, multi-objective optimization techniques such as ε-constraint method, bounded method and goal programming method etc. which are applied in RL & CLSC network design are reviewed. Then, literature review on the application of FGP-DIP in different research areas are mentioned and finally other FGP techniques such as weighted additive method, interactive FGP etc. which are used in RL & CLSC network design are discussed.

In the real life applications of RL & CLSC network design, instead of one objective as in the traditional linear programming models, there may be several conflicting objectives and this is more realistic. Decision makers can handle these objectives simultaneously while generating a solution set via the goal programming technique which was first introduced by Charnes and Cooper (1961) or other methods. However, it is emphasized that supply chain network design problem is generally modelled as a single objective problem in the literature. In other words, there are a lot of studies in RL & CLSC management using various techniques but so little use the multi-objective optimization (Wang, Lai, and Shi, 2011; Mirakhorli, 2010). Some of them are reviewed as follows.

Minimization of total cost and minimization of the total tardiness which is related to the network responsiveness were addressed as objective functions by Pishvaee and Torabi (2010). Two-phased approach based on hybridization of formerly proposed methods by Jimenez et al. (2007) and Parra et al. (2005) is used for solving the formulated CLSC network design model. The proposed model is converted into the crisp equivalent in the first phase. In the second phase, an interactive fuzzy solution approach is proposed by combining the new fuzzy multi-objective approaches of Torabi and Hassini (2008); Selim and Ozkarahan (2008).

A bi-objective mixed integer linear programming model was developed by Khajavi, Hosseini, and Makui (2011) for the capacitated multi-stage CLSC network design with the conflicting objectives of minimizing total cost and maximizing the responsiveness of the configuration. Because, opening more facilities increases the responsiveness for higher customer satisfaction degree, but has cause the larger fixed investment costs They also added the capacity levels of facilities as important decision variables and transformed the model to the single objective by using bounded method which considers the second objective as a constraint.

A mixed integer linear programming model was proposed by Zegordi, Eskandarpour, and Nikbakhsh (2011) for a bi-objective, 4-tier, 3PL post-sales RL network design for determining allocation of the repairing equipments and material flows between tiers. They tried to minimize the fixed and transportation costs as well as total weighted tardiness of returning products. In order to transform the bi-objective problem into single objective optimization problem, ε-constraint method was used.

The normalized normal constraint method which can yield a well-distributed set of all available Pareto solutions was applied by Wang, Lai, and Shi (2011) for a green supply chain network design problem where the fixed environmental investments decisions such as installation of environmental protection equipments were determined in the design phase. They introduced a new type of decision variable namely the environmental protection level of each facility. Objectives of that study are minimization of total costs and minimization of the total $CO_2$ emissions along the supply chain. Sensitivity analysis have shown that supply chain network with larger capacity provides lower costs and lower $CO_2$ emission and increasing the supply range reduced both the $CO_2$ emission and transportation costs.

Pati, Vrat, and Kumar (2008) proposed a mixed integer goal programming model for multi-product, multi-echelon and multi-facility RL distribution network problem of a paper recycling system. They considered three objectives namely: minimizing RL costs, minimizing the non-relevant waste paper in the network and maximizing the waste paper collection at the source.

Subulan and Tasan (2011a) applied goal programming technique for bi-objective, multi-echelon, multi-product CLSC network design problem with two objectives namely minimization of total costs and maximization of the collection of returned products in battery industry. They also analyzed the effects of major factors such as return fraction, maximum allowable distance and maximum number of facilities that can be opened etc. on the CLSC network design by using Taguchi experimental design method.

In goal programming models, decision maker determines the target value or achievement level for each goal. On the other hand, determination of these target values in a definite way or implicitly is generally a difficult task for the decision makers since the lack of some information or uncertainty. Therefore, goals should be stated imprecisely in the case of fuzzy decision environment. In other words, RL & CLSC network design problem is a strategic/long-range decision making process. Thus, in order to reflect the real life applications, the issue of uncertainty should be taken into account. For considering the uncertainty, various operations research techniques as mentioned earlier are available such as stochastic programming, robust optimization, possibilistic programming and fuzzy optimization.

Assessments and measurement of the total cost (in this Chapter, objective-1) is a challenging task and requires a great deal of human perception. The objective value (total cost) becomes fuzzy in character because of the fuzzy cost items such as production, transportation, collection, recycling etc. which constitute the total costs (Bilgen, 2010a). In addition, with the perspective of second objective (maximization of the collection of used batteries) since the quantities of returned batteries can be calculated through an uncertain fraction of dealer’s forecasted demand and the some information is incomplete or unobtainable regarding these parameters, this objective value should also be fuzzy in character. Finally, we consider manufacturing plants', licensed recycling facilities', depots' capacities and related weight factors for capacity utilizations while calculating the total volume flexibility in the third objective function. Therefore, fuzziness should also be considered in this objective value. Baykasoglu and Gocken (2008) refer to these models with fuzzy objectives as type-1 fuzzy mathematical programming models in their extensive classification.

In this Chapter, a MOLP model with different importance and priorities is presented by employing the approach which was developed by Chen and Tsai (2001). Chen and Tsai (2001) incorporated the different importance and preemptive priority structure of the decision maker into a single formulation by using an additive model with the objective of maximizing the sum of achievement degrees of all fuzzy goals. Some of the formerly developed FGP techniques is discussed below.

FGP approach was firstly introduced by Narasimhan (1980) with the usage of membership functions and min-operator based on fuzzy mathematical programming technique developed by Zimmermann (1978) for multi-objective optimization problems. In that model, objective function is maximizing the membership function value of least satisfied goal or constraint where there is no fundamental difference between them. An important issue in FGP problems is the reflection of the importance weights and satisfaction sequence or achievement order of some goals since they may be different for the decision makers. Linguistic terms such as 'important', 'very important', 'low important' and so on were used by Narasimhan (1980) to verbally define the relative importance of each fuzzy goal. By contrast, Tiwari, Dharmar, and Rao (1987) added the weights of each goal in the objective function as coefficients in order to consider this relative importance. However, undesirable solutions may be obtained with that method because of the changes in weights. Main disadvantage of these former methods was the computational efficiency reduction in the case of satisfaction sequences/orders (priority levels) of the goals increase. Therefore, this was the main reason for reformulation of the FGP approach by Chen and Tsai (2001). They overcome this drawback and obtained more efficient solutions by expressing the desirable achievement degrees of each fuzzy goal precisely in order to provide single formulation for priority structure. They assigned higher achievement degrees to the more important goals by using linguistic variables. Comparisons showed that obtained sum of the satisfaction degrees from that method of Chen and Tsai (2001) is greater than the other ones and has more computational superiority. This is the main reason of preferring this method for application in lead/acid battery CLSC network design problem. However, the only drawback of this method is the possibility of resulting infeasible solutions in the case of determining very high desirable achievement degrees for the goals. In this situation, a compromise solution between goals should be made by the decision maker or modification of the membership functions or model parameters may be required until satisfactory solution is provided. It is clearly understood that determination of these desirable achievement degrees is a difficult task. The approach proposed by Liou and Wang (1992) is usually used for determining the desirable achievement degrees precisely by Jamalnia and Soukhakian (2009), Belmokaddem, Mekidiche, and Sahed (2009) for consideration of only one decision maker.

There are a few studies in the literature that represent the application of FGP-DIP developed by Chen and Tsai (2001) and to the best of our knowledge, there are no researches proposed the application of this method in RL & CLSC environment so far. Some of the studies are summarized and then other FGP methods including RL & CLSC topic are given as follows.

An application of frequently mentioned approach for FGP-DIP was presented by Tsai, You, Lin, and Tsai (2008) via fuzzy mixed integer goal programming model for allocation of steel products among multiple distribution channels (Distribution channel allocation problem) with three vague goals: maximizing net profits, minimizing the rate of end users' claims and minimizing the rate of late lading, respectively. In their model, each objective has an acceptable range of aspiration value with different achievement level.

Belmokaddem, Mekidiche, and Sahed (2009) also applied this method for solving the aggregate production planning problem of an iron manufacturer considering three objectives namely minimization of total production costs, minimization of inventory holding costs and minimization of changes in workforce level. They used Liou and Wang's (1992) approach for ranking fuzzy numbers in order to determine the degree of achievement levels precisely for each fuzzy goal.

Another application of this method was performed by Jamalnia and Soukhakian (2009) to the non-linear programming model of aggregate production planning problem which integrates the learning curve effects and product life cycle concept into the model. The non-linearity of the model comes from consideration of the learning curve effects. GENOCOP III (Genetic algorithm for numerical optimization of constrained problems) is used in the solution phase of this non-linear programming model. In addition to consider quantitative objectives as in (Belmokaddem et al., 2009), a qualitative objective is determined as maximizing the customer satisfaction from the company operations and described by linguistic terms.

In order to deal with the fuzzy nature in quality function deployment process, this method was also applied by Chen and Weng (2006) to determine the necessary fulfilment levels of design requirements for achieving the maximum satisfaction degree of several goals in product design phase. Application area of FGP-DIP in the literature is limited to above studies.

Similarly, there are a few applications of other FGP methods in RL & CLSC environment. For instance, application of weighted additive method which was developed by Tiwari et al. (1987) was presented by Nukala and Gupta (2006) for strategic and tactical planning of a CLSC network where the aspiration levels of three goals namely maximizing the net profit, maximizing the revenue from recycling and minimization of disposed items are imprecise in nature. For assigning the weights to the goals, Fibonacci numbers are used.

A solution methodology based on the combination of the three algorithms: scatter search, the constraint method and dual simplex method was designed by Du and Evans (2008) for a multi-objective post-sale service CLSC network design model. Goals of their model are the minimization of the overall costs and the minimization of the total tardiness of cycle time. Zarandi, Sisakht, and Davari (2011) extended the study of Selim and Ozkarahan (2008) by adding backward flows in order to analyze the effects of reverse costs and backward service level. They considered three goals with fuzzy aspiration levels: minimizing total cost, maximizing total service level and maximizing the reverse service level and solved the problem through interactive FGP approach. Interactive FGP approach was also used by Mirakhorli (2010) to solve the multi-objective RL network design problem which also assumes that the demand and amounts of returned products were imprecise and represented by fuzzy triangular numbers. In addition to minimization of total costs, minimization of total transportation time was considered as an objective which is used for measuring customer satisfaction. The upper and lower bound of each objective were estimated by the decision maker using payoff matrix that is generated by solving the problem for each objective separately while the fuzzy constraints are in their lower and upper stream value.

All of the above studies are summarized in Tables 4.1 and 4.2, respectively.

Table 4.1 Applications of FGP technique developed by Chen and Tsai (2001)

| **Article** | **Application Study** |
|---|---|
| Tsai, You, Lin, and Tsai (2008) | "Allocation of steel products among multiple distribution channels" |
| Belmokaddem, Mekidiche, and Sahed (2009) | "Aggregate production planning of an iron manufacturer" |
| Jamalnia and Soukhakian (2009) | "Non-linear aggregate production planning with learning curve effects" |
| Chen and Weng (2006) | "Determination of necessary fulfilment levels of design requirements in QFD" |
| Subulan, Tasan, and Baykasoglu (2012a) | "Multiple objective CLSC network design in lead/acid battery sector" |

Table 4.2 Multi-objective RL & CLSC network design models

| Article | Goals | Method |
|---|---|---|
| Pishvaee and Torabi (2010) | Cost minimization and minimization of total tardiness | Interactive Fuzzy Solution Approach |
| Khajavi, Seyed-Hosseini, and Makui (2011) | Cost minimization and Maximizing the responsiveness of configuration | Bounded Method |
| Zegordi, Eskandarpour, and Nikbakhsh (2011) | Minimizing fixed and transportation costs and total weighted tardiness of returned products | ε- Constraint Method |
| Wang, Lai, and Shi (2011) | Minimization of total cost and minimization of the total $CO_2$ emissions | Normalized Normal Constraint Method |
| Subulan and Tasan (2011a) | Minimization of total cost and maximization of collection coverage | Goal Programming |
| Nukala and Gupta (2006) | Maximizing net profit, maximizing revenue obtained from recycling and minimizing disposed items | Weighted Additive Method |
| Du and Evans (2008) | Minimization of the overall costs and minimization of total tardiness of cycle time | Combination of Scatter Search, Constraint Method and Dual Simplex Method |
| Zarandi, Sisakht, and Davari (2011) | Minimizing total cost, maximizing total service level and maximizing reverse service level | Interactive Fuzzy Goal Programming |
| Mirakhorli (2010) | Minimization of total cost and total transportation time of the system | Interactive Fuzzy Goal Programming |
| Subulan, Tasan, and Baykasoglu (2012a) | Minimization of total CLSC cost, maximization of total coverage of returned products and total volume flexibility | FGP-DIP developed by Chen and Tsai (2001) |
| Subulan, Tasan and Baykasoglu (2012b) | Maximization of total CLSC profit, minimization of total environmental impact along the CLSC | Interactive Fuzzy Goal Programming |

## 4.4 Mathematical Model Development

### *4.4.1 Problem Description and Assumptions*

Lead/acid battery sector requires an optimal design for the CLSC network. The general scheme of the CLSC network structure is shown in Figure 4.1. In this research, not only opening of regional wholesalers for forward flows of newly produced batteries and the setting up of the collection centers for reverse flows, but also a hybrid facility which undertakes the transfer of both forward and returned batteries are taken into account as in the model developed by Lee, Dong, and Bian (2010). Thus, the facilities will be opened in the candidate locations have to be one of these three alternative facility types. In this case, hybrid facilities are both regional wholesalers which market the new batteries for meeting the customers' demand and initial collection points which collect the spent batteries from the retailers or service outlets, store for up to several days and then send to the licensed recycling facilities.

In the forward supply chain, in addition to provide some materials from the recycling way, the main components of a lead acid battery such as battery pole posts, plate, metallic grid, lead oxide, electrolyte, polypropylene casing (Kannan, Sasikumar, and Devika, 2010) are purchased from different vendors for new battery production. Once the battery is produced in different new battery manufacturers it has to be distributed via regional wholesalers or hybrid facilities to the dealers, retailers or authorized automotive services and then end users.

In the reverse supply chain, the end user leaves the spent battery at the retailer or dealer where it is replaced by a new one at the end of battery use. Therefore, we can designate the retailers or dealers as initial collection points. Then the collected spent batteries are transported the licensed recycling facilities through collection centres or hybrid facilities. Furthermore, collection centres and hybrid facilities can be considered as a temporary storage area for the returned batteries. Before the transhipping, used batteries are controlled in terms of quality specifications for recycling process. According to the controlling process, the useless batteries are disposed off and the appropriate batteries for recycling are shipped to the licensed recycling facilities which are secondary lead smelters and plastic recyclers. In accordance with the need for spent battery, additional used batteries can be purchased from the scrap dealers which are certificated with temporary storage permission. After the recycling process, the lead and plastic parts are transported to the new battery manufacturers where secondary lead and recycled plastic are used with the virgin lead and plastic. The spent sulphuric acid is sold to the third party for chemical production, fertilizer production, pigment production and pesticide industry etc. (Kannan, Sasikumar, and Devika, 2010).

The proposed mathematical model will be developed based on the following assumptions.

- In the developed network design model, decision makers have imprecise goals such as “total CLSC costs should be approximately less than some value”, “amounts of collected spent batteries should be approximately greater than some value” or “total volume flexibility should be greater than some value”. This imprecise nature is actually fuzziness rather than randomness. Therefore, aspiration levels of the goals are stated as fuzzy, constraints of the proposed model assumed to be crisp.
- Continuous linear membership functions are used for each of the objectives based on the payoff table.
- There are two different options for the new battery manufacturers to supply components such as lead, plastic etc. One is purchasing them from different suppliers; and the other is acquiring them by recycling from the licensed recycling facilities.
- Shortages and inventory holding are not allowable and cost parameters at all stages of the CLSC network do not change.
- Transportation lead times between the stages are not taken into account because of the single period consideration.
- The dealers’ or retailers’ demand forecasts are known and deterministic.

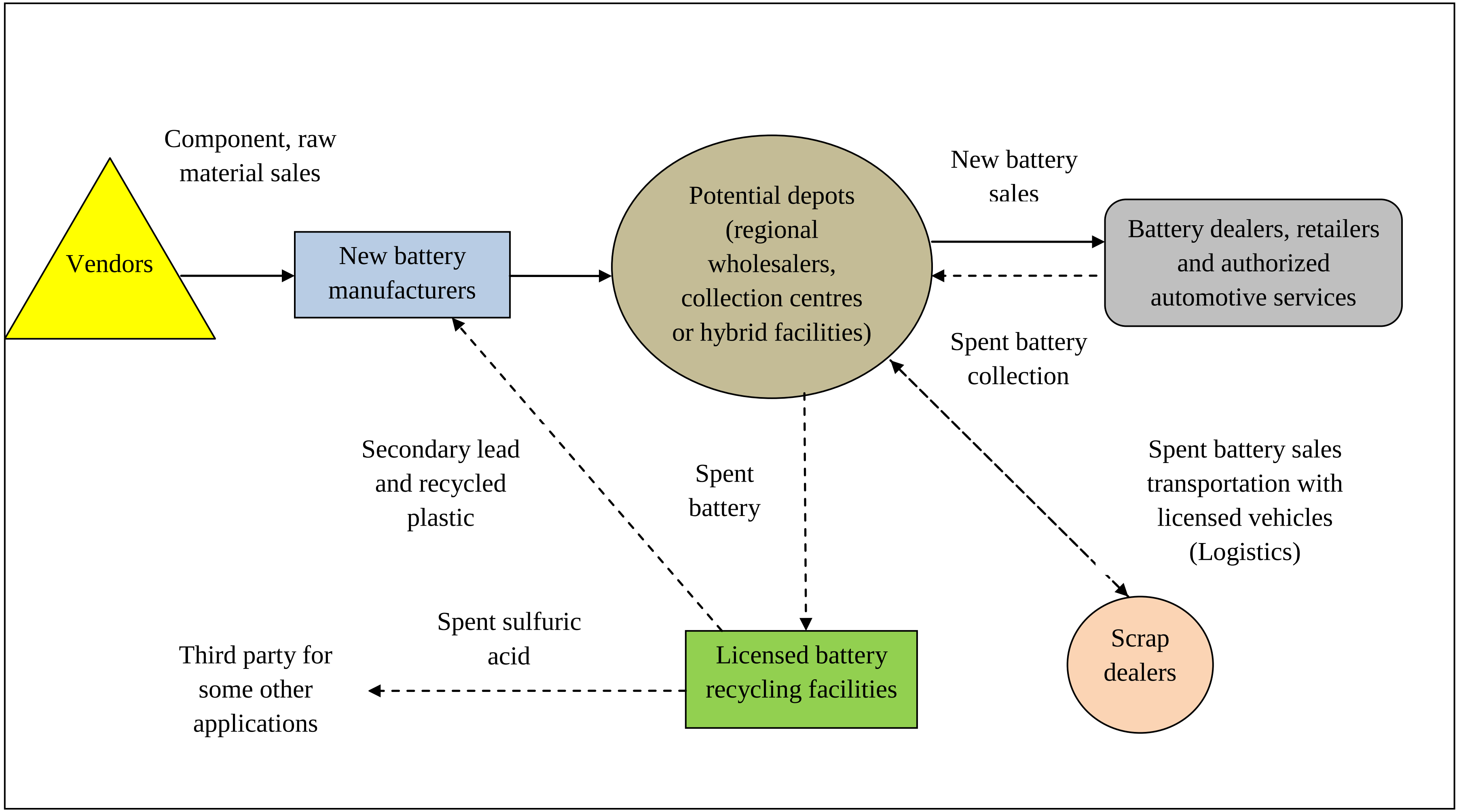



Figure 4.1 A depiction of the CLSC network for the lead/acid battery recovery

- Quantity of returned batteries from a given dealer or retailer is the fraction of total demand of that dealer or retailer.
- Purchasing and selling of same type used batteries cannot be done at the same time for each collection center and hybrid facility and at most one alternative can be done.
- It is assumed that scrap dealers have an infinite capacity and budget for used battery sales or purchasing.

#### *4.4.2 Indices and Sets*

$b$ set of battery type $b \in B$

$c$ set of component type $c \in C$

$i$ set of new battery manufacturers $i \in I$

$j$ set of potential depots such as regional wholesalers, collection centers or hybrid facilities $j \in J$

$k$ set of battery dealers, retailers or authorized automotive services $k \in K$

$l$ set of potential licensed recycling facilities $l \in L$

$v$ set of vendors $v \in V$

#### *4.4.3 Model Parameters*

$f1_j$ fixed set-up cost of the regional wholesaler $j$

$f2_j$ fixed set-up cost of the collection center $j$

$f3_j$ fixed set-up cost of the hybrid facility $j$

$f4_l$ fixed set-up cost of the licensed recycling facility $l$

$PRC_b$ production cost of one unit of battery type-*b* in each new battery manufacturer

$TC_b$ transportation cost of one unit of battery type-*b* per kilometer

$TC1_b$ transportation cost of one unit of used battery type-*b* per kilometer

$TC_c$ transportation cost of material/component type-*c* in kilograms per kilometer

$PUC_{cvi}$ purchasing cost of material/component type-*c* in kilograms from vendor *v* for manufacturer *i*

$PC_{bj}$ purchasing cost of one unit of used battery type-*b* from any scrap dealer for depot *j*

$SP_{bj}$ selling price of one unit of used battery type-*b* from depot *j* to any scrap dealer

$RC_{bl}$ recycling cost per unit of used battery type-*b* in licensed recycling facility *l*

$CC_b$ collection cost per unit of spent battery type-*b*

$DIC_b$ disposal cost per unit of un-recyclable battery type-*b*

$DE_{bk}$ demand of battery dealer or retailer *k* for battery type- *b*

$S_b$ returned fraction of demand for battery type-*b* from battery dealers or retailers

$a_{jk}$ binary parameter is equal to 1, if the distance between the battery dealer *k* and collection center or hybrid facility *j* is within the maximum acceptable distance. 0, otherwise

$\alpha_b$ disposal rate for battery type-*b*

$\gamma_b$ recycling rate for battery type-*b*

$W_b$ weight of the used battery type-*b*

$\varepsilon_{cb}$ percentage of contribution of material/component type-*c* for the used battery type-*b*

$\rho_{cb}$ amount of material/component type-*c* to produce one unit of new battery type-*b*

$cap^f_{bj}$ capacity of regional wholesaler *j* for forward flows of newly produced battery type-*b*

$hcap^f_{bj}$ capacity of hybrid facility *j* for forward flows of newly produced battery type-*b*

$cap^r_{bj}$ capacity of collection center *j* for reverse flows of spent battery type-*b*

$hcap^r_{bj}$ capacity of hybrid facility *j* for reverse flows of spent battery type-*b*

$Prcap_{bi}$ production capacity of new battery manufacturer *i* for battery type-*b*

$REcap_{bl}$ recycling capacity of licensed recycling facility *l* for used battery type-*b*

$Vcap_{cv}$ supply capacity of vendor *v* for material/component type-*c*

$d1_{ij}$ the distance between new battery manufacturer *i* and depot *j*

$d2_{jk}$ the distance between depot *j* and battery dealer or retailer *k*

$d3_{jl}$ the distance between depot *j* and licensed recycling facility *l*

$d4_{li}$ the distance between licensed recycling facility *l* and new battery manufacturer *i*

*DMAX* maximum allowable distance from a given regional wholesaler or hybrid facility to a battery dealer or retailer for new battery distribution

*D1MAX* maximum allowable distance from a given battery dealer or retailer to a collection center or hybrid facility for used battery collection

*W1* weight factor for capacity utilization of manufacturing plants

*W2* weight factor for capacity utilization of regional wholesalers and hybrid facilities for performing forward flows

*W3* weight factor for capacity utilization of licensed recycling facilities

*W4* weight factor for capacity utilization of collection centers and hybrid facilities for performing reverse flows

*N* maximum number of opened collection centers and hybrid facilities

*M* an arbitrary set large number

### *4.4.4 Decision Variables*

$w_j$ the indicator of opening regional wholesaler *j*

$c_j$ the indicator of opening collection center *j*

$h_j$ the indicator of opening hybrid facility *j*

$r_l$ the indicator of opening licensed recycling facility *l*

$Q_{bi}$ production quantity of battery type-*b* in new battery manufacturer *i*

$x_{bijk}$ quantity of battery type-*b* shipped from new battery manufacturer *i* via regional wholesaler or hybrid facility *j* to the battery dealer *k*

$x1_{bkjl}$ quantity of used battery type-*b* shipped from battery dealer *k* via collection center *j* or hybrid facility *j* to the licensed recycling facility *l*

$x2_{cli}$ quantity of material/component type-*c* shipped to new battery manufacturer *i* from licensed recycling facility *l*

$QP_{cvi}$ amount of material/component type-*c* purchased from vendor *v* by new battery manufacturer *i*

$q_{bjl}$ quantity of used battery type-*b* purchased by depot *j* (Hybrid facility or collection center) from any scrap dealer and sent to the licensed recycling facility *l*

$q1_{bj}$ quantity of used battery type-*b* sold to any scrap dealer from depot *j*

$RE_{bl}$ recycling quantity of used battery type-*b* at the licensed recycling facility *l*

$y_{jk}$ 1, if regional wholesaler or hybrid facility *j* serves battery dealer *k*; 0, otherwise

$y1_{kj}$ 1, if collection centre or hybrid facility *j* serves battery dealer *k*; 0, otherwise

$y_{bj}$ 1, if depot *j* purchases used battery type-*b* from any scrap dealer; 0, otherwise

$y1_{bj}$ 1, if depot *j* sells used battery type-*b* to any scrap dealer; 0, otherwise

### *4.4.5 Mathematical Formulation of the Problem*

We developed a MOLP model with three objectives namely minimization of the total CLSC costs, maximization of the collection of returned batteries through opened collection centers or hybrid facilities as in the well known maximal coverage problem in the literature and maximization of total volume flexibility. The objective functions are defined as follows:

(i) The first objective function is to minimize the total CLSC costs which consist of fixed opening costs, production costs, transportation costs, purchasing costs, recycling costs, collection costs and disposal costs as represented in equation (4.1).

$$Min\ Z_1 \cong \sum_{j}^{J} f1_j\,.w_j + \sum_{j}^{J} f2_j.c_j + \sum_{j}^{J} f3_j.h_j + \sum_{l}^{L} f4_l.r_l + \sum_{c}^{C}\sum_{v}^{V}\sum_{i}^{I} QP_{cvi}\,.PUC_{cvi}$$

$$+ \sum_{b}^{B}\sum_{j}^{J}\sum_{i}^{I}\sum_{k}^{K} x_{bijk}\,.TC_b.\left(d1_{ij} + d2_{jk}\right) + \sum_{b}^{B}\sum_{k}^{K}\sum_{j}^{J}\sum_{l}^{L} x1_{bkjl}\,.TC1_b.\left(d2_{jk} + d3_{jl}\right)$$

$$+ \sum_{b}^{B}\sum_{j}^{J}\sum_{l}^{L} q_{bjl}\,.TC1_b.d3_{jl} + \sum_{c}^{C}\sum_{l}^{L}\sum_{i}^{I} x2_{cli}\,.TC_c.d4_{li} + \sum_{b}^{B}\sum_{i}^{I} Q_{bi}\,.PRC_b$$

$$+ \sum_{b}^{B}\sum_{j}^{J} q_{bjl}\,.PC_{bj} - \sum_{b}^{B}\sum_{j}^{J} q1_{bj}.SP_{bj} + \sum_{b}^{B}\sum_{l}^{L} RE_{bl}\,.RC_{bl} + \sum_{b}^{B}\sum_{j}^{J}\sum_{k}^{K} y1_{kj}.DE_{bk}\,S_b.CC_b$$

$$+\sum_{b}^{B}\sum_{j}^{J}\sum_{k}^{K}\sum_{l}^{L}(x1_{bkjl} + q_{bjl} - q1_{bj}).\alpha_b.DIC_b \quad (4.1)$$

(ii) The second objective function is to maximize the coverage of collected batteries by opened collection centers or hybrid facilities as represented in equation (4.2). Formulation of this goal is motivated based on the well known problem in the literature as “maximal coverage problem”. The main aim of the maximal covering problem is locating a fixed numbers of facilities within the acceptable distance while maximizing the amount of demand covered. As described, maximal covering problem considers the resources available such as financial resources, fixed investments etc. (in terms of the number of facilities we are able to locate) and determines the maximum demand coverage possible. Maximal covering location problem (MCLP) is defined by Davari, Zarandi, and Hemmati (2011) as “investigating the location of a number of facilities on a network in order to maximize the covered population”. For covering a population, at least one facility must be opened within a pre-defined distance of it.

$$Max\ Z_2 \cong \sum_{b}^{B}\sum_{k}^{K}\sum_{j}^{J} DE_{bk}\ .S_b.y1_{kj} \quad (4.2)$$

(iii) The third objective function is to maximize the total volume flexibility which consists of manufacturing or plant volume flexibility and distribution volume flexibility as represented in equation (4.3). Volume flexibility is expressed by Sabri and Beamon (2000) as the ability to change the level of produced products and this can be commonly measured by capacity slack. Plant or manufacturing volume flexibility is measured as “the difference between plant capacity and plant capacity utilization”. In addition, distribution volume flexibility can be calculated as the difference between the available throughput of the regional wholesalers’ or hybrid facilities’ and demand requirements of the dealers or retailers. Recycling and collection volume flexibility should also be added to the total volume flexibility as an important part of this objective in RL & CLSC environment due to the nature of reverse flows.

$$Max\ Z_3 \cong W1.\sum_{i}^{I}(\sum_{b}^{B} Prcap_{bi} - \sum_{b}^{B} Q_{bi}) + W2.\sum_{j}^{J}(\sum_{b}^{B} cap_{bj}^{f}.w_j + hcap_{bj}^{f}.h_j - \sum_{b}^{B}\sum_{k}^{K} y_{jk}.DE_{bk}) + W3.\sum_{l}^{L}(\sum_{b}^{B} REcap_{bl}.r_l - \sum_{b}^{B} RE_{bl}) + W4.\sum_{j}^{J}(\sum_{b}^{B} cap_{bj}^{r}.c_j + hcap_{bj}^{r}.h_j - \sum_{b}^{B}\sum_{k}^{K} y1_{kj}.DE_{bk}.S_b - \sum_{b}^{B}\sum_{l}^{L} q_{bjl}) \tag{4.3}$$

These goals should be satisfied simultaneously and it must be provided an efficient compromise solution by the decision makers in the framework of fuzzy aspiration levels. Where the symbol $\cong$ fuzzified version of $=$ and refers to the fuzzification of the aspiration levels of the decision makers. Constraints included in this model are expressed by equations (4.4) to (4.28).

$$\sum_{j}^{J} c_j + h_j \leq N \tag{4.4}$$

$$y1_{kj} \leq a_{jk}.(c_j + h_j) \qquad \forall j, \forall k \tag{4.5}$$

$$\sum_{k}^{K} y_{jk} \leq M.(h_j + w_j) \qquad \forall j \tag{4.6}$$

$$\sum_{j}^{J} y1_{kj} \leq 1 \qquad \forall k \tag{4.7}$$

$$\sum_{j}^{J} y_{jk} = 1 \qquad \forall k \tag{4.8}$$

$$\sum_{k}^{K} y_{jk}.DE_{bk} \leq cap_{bj}^{f}.w_j + hcap_{bj}^{f}.h_j \qquad \forall b, \forall j \tag{4.9}$$

$$\sum_{i}^{I} x_{bijk} = DE_{bk}.y_{jk} \qquad \forall b, \forall k, \forall j \tag{4.10}$$

$$\sum_{k}^{K} y1_{kj}.DE_{bk}.S_b + \sum_{l}^{L} q_{bjl} - q1_{bj} \leq cap_{bj}^{r}.c_j + hcap_{bj}^{r}.h_j \qquad \forall b, \forall j \tag{4.11}$$

$$\sum_{l}^{L} x1_{bkjl} = y1_{kj}.DE_{bk}.S_b \qquad \forall b, \forall k, \forall j \tag{4.12}$$

$$w_j + c_j + h_j \leq 1 \qquad \forall j \tag{4.13}$$

$$\sum_{j}^{J}\sum_{k}^{K} x_{bijk} \leq Q_{bi} \qquad \forall b, \forall i \tag{4.14}$$

$$Q_{bi} \leq Prcap_{bi} \qquad \forall b, \forall i \tag{4.15}$$

$$\left\{\sum_{k}^{K}\sum_{j}^{J} x1_{bkjl} + \sum_{j}^{J} q_{bjl} - \sum_{j}^{J} q1_{bj}\right\}.(1-\alpha_b) = RE_{bl} \qquad \forall b, \forall l \tag{4.16}$$

$$\sum_{i}^{I} x2_{cli} = \sum_{b}^{B} RE_{bl}.\gamma_b.W_b.\varepsilon_{cb} \qquad \forall c, \forall l \tag{4.17}$$

$$\sum_{l}^{L} q_{bjl} \leq M.y_{bj} \qquad \forall b, \forall j \tag{4.18}$$

$$q1_{bj} \leq M.y1_{bj} \qquad \forall b, \forall j \tag{4.19}$$

$$y_{bj} + y1_{bj} \leq 1 \qquad \forall b, \forall j \tag{4.20}$$

$$d2_{jk}.y_{jk} \leq DMAX \qquad \forall j, \forall k \tag{4.21}$$

$$d2_{jk}.y1_{kj} \leq D1MAX \qquad \forall j, \forall k \tag{4.22}$$

$$\sum_{v}^{V} QP_{cvi} + \sum_{l}^{L} x2_{cli} = \sum_{b}^{B} Q_{bi}.\rho_{cb} \qquad \forall c, \forall i \tag{4.23}$$

$$RE_{bl} \leq REcap_{bl}.r_l \qquad \forall b, \forall l \tag{4.24}$$

$$x1_{bkjl} + q_{bjl} \leq M.r_l \qquad \forall b, \forall k, \forall j, \forall l \tag{4.25}$$

$$\sum_{i}^{I} QP_{cvi} \leq Vcap_{cv} \qquad \forall c, \forall v \tag{4.26}$$

$$w_j, c_j, h_j, r_l, y_{jk}, y1_{kj}, y_{bj}, y1_{bj} \in (0,1) \tag{4.27}$$

$$x_{bijk}, x1_{bkjl}, q_{bj}, q1_{bj} \geq 0 \text{ and integer}. \tag{4.28}$$

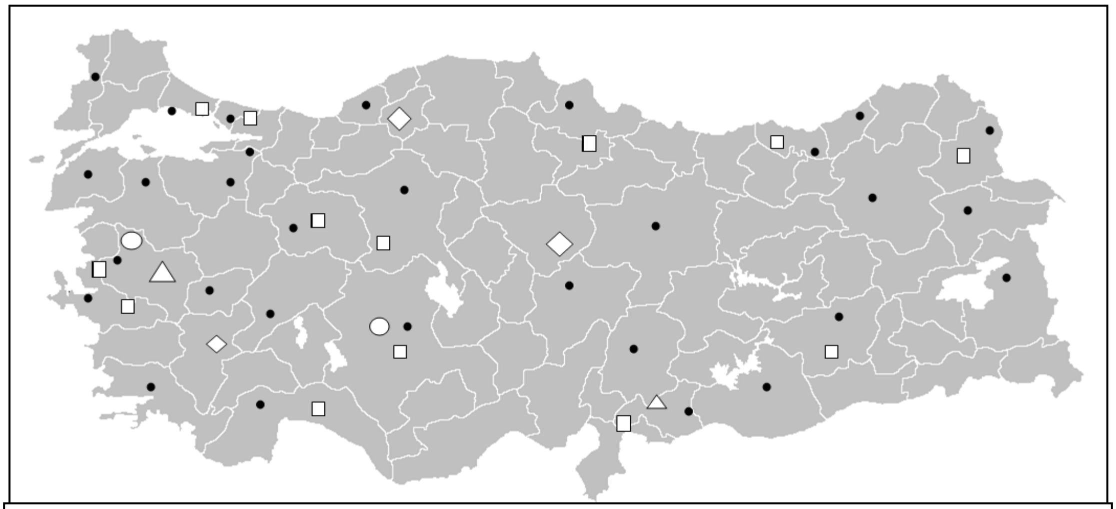
*All other variables are continuous.*

Constraint (4.4) limits the number of collection centers or hybrid facilities to be opened for spent battery returns. Constraint (4.5) determines which battery returns are covered within the acceptable service distance. Service means collection of used batteries from the retailers/dealers. If no collection center or hybrid facility is located, the right hand side of that constraint will be zero and forces the $y1_{kj}$ equal to zero. According to the constraint (4.6) if a regional wholesaler or hybrid facility is opened, it may serves to any dealer or retailer. In other words, there may be an outgoing flow (distribution operation) from this depot to the dealers. Constraint (4.7) assures that a battery dealer may be assigned to at most a single collection centre or hybrid facility for spent battery returns. Since these assignments may be impossible because of the logic of maximal covering problem, $\leq 1$ is used in that constraint set. Constraint (4.8) assures that a battery dealer is assigned to a single regional wholesaler or hybrid facility for forward flow of newly produced batteries. In other words, demands of the battery dealers must be satisfied by a single regional wholesaler or hybrid facility. Constraint (4.9) limits the number of newly produced batteries shipped through the regional wholesaler or hybrid facility to its capacity of performing forward flows. Constraint (4.10) maintains that the demands of battery dealers' for newly produced batteries must be satisfied. Constraint (4.11) restricts the number of returned batteries transferred through a collection centre or hybrid facility to its capacity of performing reverse flows. Constraint (4.12) ensures that volume of returned batteries from a given dealer or retailer is the fraction of total demand of that dealer or retailer. Constraint (4.13) ensures that at most one type of facility (regional wholesaler, collection centre or hybrid facility) can be opened at the potential depot locations. Constraint (4.14) guarantees that the outgoing flows from a new battery manufacturer cannot exceed the production quantity at that manufacturer. Constraint (4.15) ensures that the production quantity of each battery type must not get over the production capacity of the new battery manufacturers. According to constraint (4.16), one can calculate the quantity of used batteries that are recyclable. Constraint (4.17) is the conservation of flow constraint for the licensed recycling facilities. Constraint (4.18) and (4.19) provide that the variables related to quantities must take value in the case of used battery purchasing from the scrap dealers or sales of used batteries to the scrap dealers. Constraint (4.20) ensures that purchasing and selling of same type used batteries cannot be done at the same time. At most one of these variables can take a value. Constraint (4.21) and (4.22) assure that each regional wholesaler, collection centre or hybrid facility should be located within acceptable proximity of battery dealers. Constraint (4.23) is balance equation for the components that are used in the new battery production. Constraint (4.24) and (4.26) are capacity constraints for the licensed recycling facilities and vendors, respectively. Constraint (4.25) makes sure that if a licensed recycling facility is opened at the candidate location, there may be incoming flows of used batteries from the collection centers, hybrid facilities or scrap dealers to this recycling facility. Constraint (4.27) represents the binary variables. Finally, constraint (4.28) enforces the non-negativity restrictions. Transportation variables and variables correspond to spent battery purchasing/sale should take integer values since they are subject to disjunctive constraints (Kreipl and Pinedo, 2004).

## 4.5 Model Implementation

### *4.5.1 Computational Case Study and Data Description*

In order to observe the performance of the proposed FMOLP model, an illustrative example is generated based on inspiration from a lead/acid battery CLSC in Turkey. Configuration of the computational case study is shown in Figure 4.2. There are three types of batteries, three types of components, two new battery manufacturers, three vendors to supply components/raw materials, thirty dealers or retailers with uniformly distributed yearly demands, thirteen potential sites for collection, distribution or both activities as hybrid facilities and two alternatives for licensed recycling facilities in the case study.



△ New battery manufacturers
○ Potential licensed recycling facilities
□ Potential depots (Regional wholesalers, collection centers or hybrid facilities)
● Battery dealers, retailers or authorized automotive services
◇ Vendors

Figure 4.2 Configuration of the computational case study

Parameter intervals used in the computational case study are given in Table 4.3.

Table 4.3 Data ranges used in the illustrative example

| Parameters | Range of values |
|---|---|
| Demand forecasts of battery dealers | Uniform distribution (500, 2500) |
| Unit production cost | 25-65 |
| Unit transportation cost for newly produced batteries | 0.001-0.003 |
| Unit transportation cost for used batteries | 0.002-0.004 |
| Unit transportation cost for materials/components | 0.008-0.015 |
| Unit recycling cost | 7-20 |
| Unit collection cost | 2-5 |
| Unit disposal cost | 1-3 |
| Unit purchasing cost of used batteries from scarp dealers | 5-14 |
| Unit selling price of used batteries to scrap dealers | 5-14 |
| Unit purchasing cost for materials/components from vendors | 0.7-4 |
| Maximum number opened collection centers and hybrid facilities | 5 |
| Fixed cost of opening regional wholesaler | 150000-230000 |
| Fixed cost of opening collection centres | 90000-150000 |
| Fixed cost of opening hybrid facilities | 360000-522000 |
| Fixed cost of opening licensed recycling facilities | 550000-600000 |
| Production capacity of battery manufacturers | 28000-56000 |
| Capacity of regional wholesalers | 7500-15000 |
| Capacity of collection centers | 10000-20000 |
| Capacity of hybrid facilities for forward flows | 5250-10500 |
| Capacity of hybrid facilities for reverse flows | 7000-14000 |
| Capacity of licensed recycling facilities | 70000-130000 |
| Capacity of vendors | 50000-90000 |
| Return fraction | %70-%90 |
| Disposal rate | %5-%10 |
| Recycling rate | %70-%80 |
| Weight of used batteries | 15-35 |
| Contribution percentages of materials/components | %10-%55 |
| Distances | 0-1650 |
| Max. acceptable distances | 400-500 |
| Weight factors for capacity utilizations | 0.25 |

The proposed FMOLP model for network design of the CLSC aims obtaining an optimal network structure which includes best locations of regional wholesalers, collection centers, hybrid facilities and licensed recycling facilities. When the model is run with these data through a mixed integer programming solver ILOG OPL Studio version 6.3 including CPLEX 12.1.0 product on an Intel Core i7 2 GHz IBM PC for both the first objective function, second and third one separately as a single objective integer programming model, the following optimization results and independent objective function values are obtained as shown in Table 4.4.

Table 4.4 Optimization results of the deterministic model solution considering objective functions separately

| | Total cost objective-1 | Total coverage objective-2 | Total volume flexibility objective-3 |
|---|---|---|---|
| Total number of variables | 5741 | 5741 | 5741 |
| Total number of integer variables | 4797 | 4797 | 4797 |
| Total number of binary variables | 899 | 899 | 899 |
| Total number of constraints | 6179 | 6179 | 6179 |
| Total number of iterations | 72094 | 2112 | 14106 |
| Total cost of the CLSC | $11501302.99(IP solution) | $14587000 | $15374000 |
| LP relaxation value | $11501302.99 | 90043 units | 207433.4 units |
| Total maximal coverage | 87808 units | 90043 units (IP solution) | 77951 units |
| Total volume flexibility | 100390 units | 202750 units | 207433.4 units (IP solution) |
| CPU time (second) | 9.52 | 0.92 | 1.02 |
| Optimality gap (%) | - | - | - |
| Number of opened regional wholesalers | 6 | 8 | 8 |
| Number of opened collection centres | 5 | 1 | - |
| Number of opened hybrid facilities | - | 4 | 5 |
| Number of opened licensed recycling facilities | 1 | 2 | 2 |

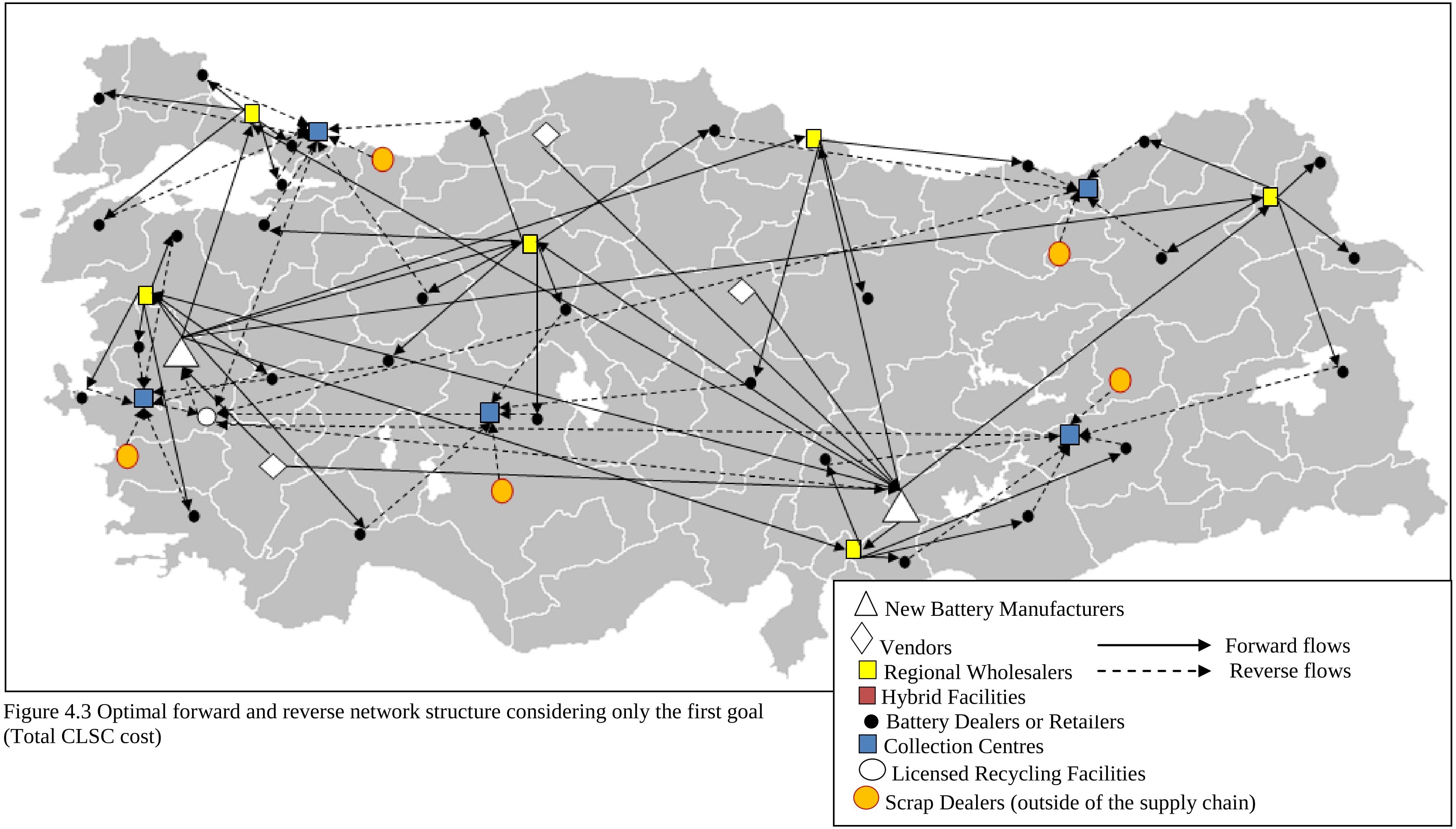



Figure 4.3 Optimal forward and reverse network structure considering only the first goal (Total CLSC cost)

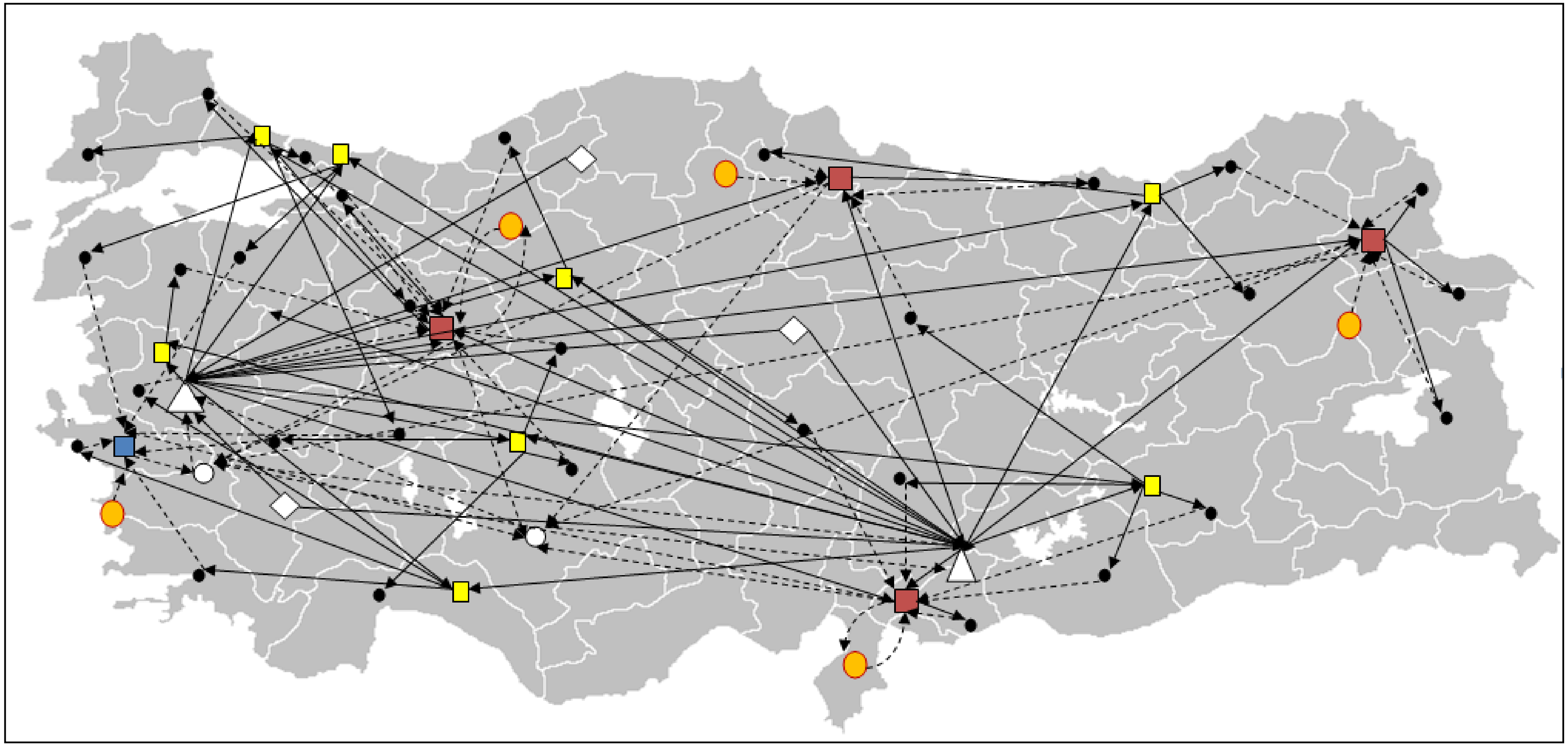


Figure 4.4 Optimal forward and reverse network structure considering only the second goal (Total collection coverage)

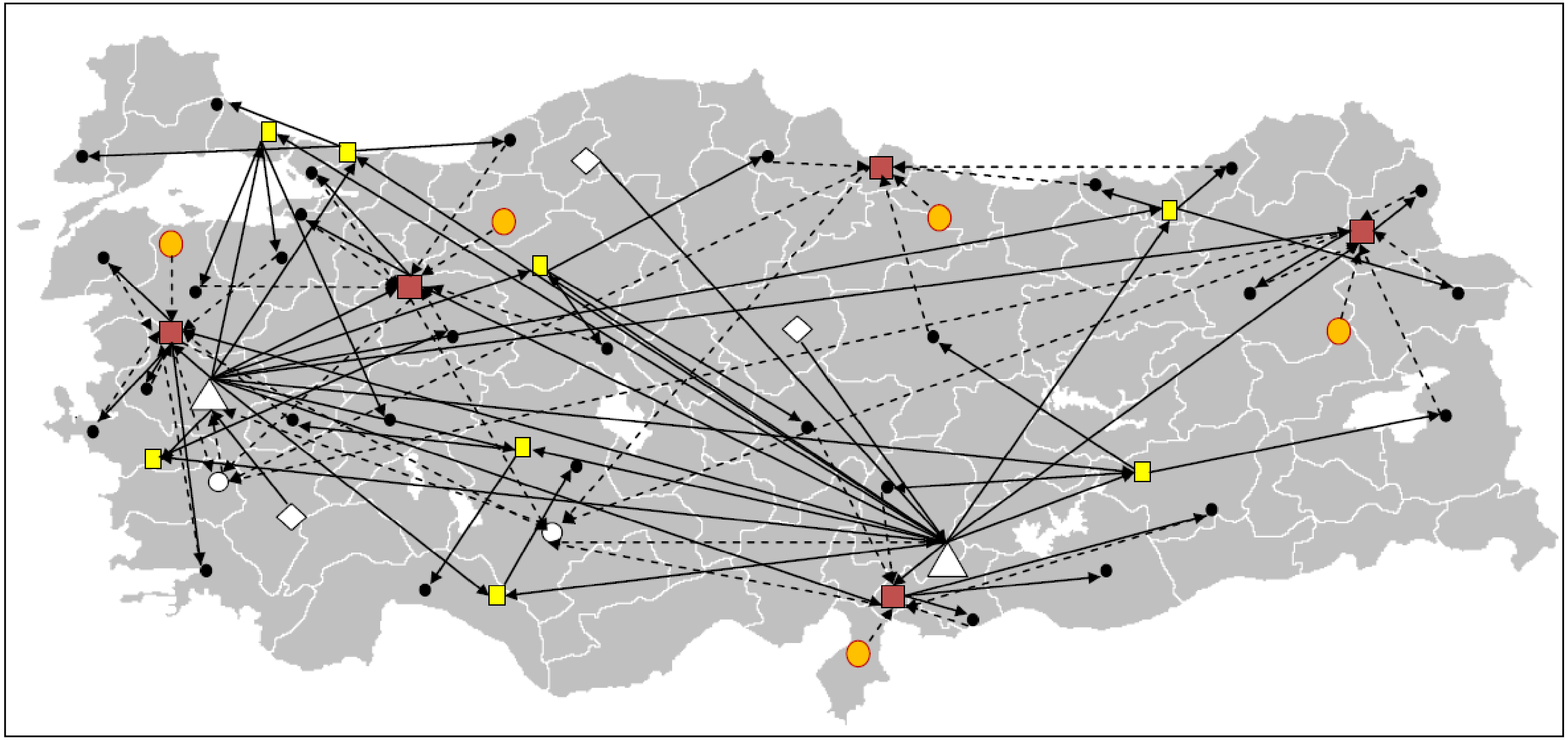


Figure 4.5 Optimal forward and reverse network structure considering only the third goal (Total volume flexibility)

In addition, corresponding optimal network structures to each objective are represented in Figures 4.3, 4.4 and 4.5. According to the Figure 4.3, both forward and reverse flows are performed between the nodes which are closest to each other as possible to minimize the transportation costs. It is also seen that all of the collection centres only purchased additional spent batteries from the scrap dealers for obtaining the cost advantage. As well as purchasing from vendors, all new battery manufacturers meet their component requirements from the licensed recycling facility-1 which is opened.

On the other hand, it is obviously seen that in order to collect spent batteries as much as possible, network configuration has spread to farther distances as shown in Figure 4.4. As well as purchasing spent batteries from the scrap dealers, spent batteries with different types are sold to scarp dealers by some hybrid facilities. There are component flows from the opened first and second licensed recycling facilities to the all new battery manufacturers.

According to Figure 4.5, only spent battery purchasing is available from the scrap dealers similar with the first objective. In addition, since the reverse flow capacities of the hybrid facilities are much more than the collection centres, only hybrid facilities are opened in case of considering third objective independently.

## 4.6 FGP-DIP for the Strategic Planning of a Lead/Acid Battery CLSC

Multi-objective, multi-echelon and multi-product linear programming model for the network design problem of a lead/acid battery CLSC can be converted to FMOLP model by displaying membership functions to represent the fuzzy goals of decision makers. In this study, it is assumed that all of the objectives defined earlier have different importance and priorities.

### *4.6.1 Construction of the membership functions*

After solving the deterministic model with each objective function independently, obtained solutions which are given in Table 4.4 are used as benchmark to construct membership functions by the decision makers. Membership functions of the fuzzy goals are defined on the interval [0, 1] and if the membership function value of $k^{th}$ goal is equal to 1, we can say that decision maker is fully satisfied. Otherwise, the membership function takes a value between 0 and 1. In the literature and practice, generally, linear membership functions are used. For defining the membership functions of each fuzzy objective, FGP requires determination of the aspiration levels and max-min limits of these goals. Generally, decision makers estimate the lower and upper limits based on their knowledge and experience. These max-min limit values estimated by Mirakhorli (2010) and Selim and Ozkarahan (2008) using the payoff table (see Table 4.5) and guaranteed the feasibility of each fuzzy goal in the solution phase.

Table 4.5 The payoff table

| | $Z_1(X)$ | $Z_2(X)$ | ........ | $Z_k(X)$ |
|---|---|---|---|---|
| $X^{(1)}$ | $Z_{11}$ | $Z_{12}$ | .......... | $Z_{1k}$ |
| $X^{(2)}$ | $Z_{21}$ | $Z_{22}$ | .......... | $Z_{2k}$ |
| . | . | . | . | . |
| . | . | . | . | . |
| . | . | . | . | . |
| $X^{(k)}$ | $Z_{k1}$ | $Z_{k2}$ | .......... | $Z_{kk}$ |

Here, $Z_k(X)$ is the $k^{th}$ objective function and $X^{(k)}$ is its optimal solution. The payoff matrix can be derived by solving the problem $k$-single objective with $X^{(k)}$ ($k$=1,2,...K) solution vectors or in other words, putting the optimal value to other objective functions. So, the main diagonal in this matrix denotes the individual best solutions of each objective. Then, the limits can be determined for minimization and maximization problems as in following equations, respectively.

Limit values for minimization problems:

$$Z_k^l = Z_{kk}$$
$$Z_k^u = \max(Z_{k1}, Z_{k2}, \dots \dots Z_{kk}) \quad (4.29)$$

Limit values for maximization problems:

$$Z_k^u = Z_{kk}$$
$$Z_k^l = \min(Z_{k1}, Z_{k2}, \dots \dots Z_{kk}) \quad (4.30)$$

By using the results in Table 4.4, payoff table of the current problem can be derived as in Table 4.6.

Table 4.6 Corresponding payoff table

| Objectives | Total CLSC cost | Total coverage of collected spent batteries | Total volume flexibility |
|---|---|---|---|
| **Total CLSC cost** | $11501302.99 | 87808 units | 100390 units |
| **Total coverage of collected spent batteries** | $14587000 | 90043 units | 202750 units |
| **Total volume flexibility** | $15374000 | 77951 units | 207433.4 units |

Then, lower and upper bounds can be determined as in Table 4.7 in order to use in the construction of membership functions for satisfaction levels of the goals.

Table 4.7 Limits for the objectives

| Objectives | Lower bound | Upper bound |
|---|---|---|
| **Total CLSC cost** | $11501302.99 | $15374000 |
| **Total coverage** | 77951 units | 90043 units |
| **Total volume flexibility** | 100390 units | 207433.4 units |

To quantify the fuzzy aspiration levels of the objectives, linear and continuous membership functions are found appropriate. The membership function of each fuzzy goal and regarding analytical definitions are shown as in the following Figures 4.6, 4.7 and 4.8 based on Zimmermann (1976).

$\mu_{Z_1}$

$$\mu_{Z_1} = \begin{cases} 1, & if\ Z_1 \leq 11501302 \\ \frac{11501302 - Z_1}{15374000 - 11501302}, & if\ \ 11501302 \leq Z_1 \leq 15374000 \\ 0, & if\ \ Z_1 \geq 15374000 \end{cases} \tag{4.31}$$

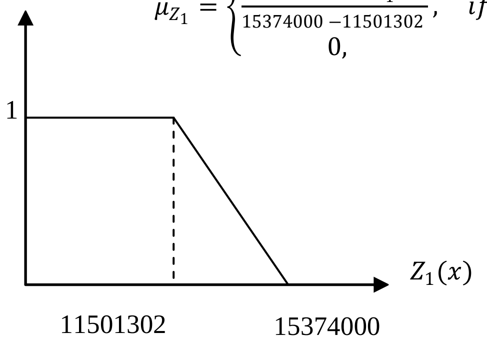



Figure 4.6 Membership function of fuzzy minimum $Z_1$ (Minimize the total costs of the CLSC)

$\mu_{Z_2}$

$$\mu_2 = \begin{cases} 1, & if\ Z_2 \geq 90043 \\ \frac{Z_2 - 77951}{90043 - 77951}, & if\ \ 77951 \leq Z_2 \leq 90043 \\ 0, & if\ \ Z_2 \leq 77951 \end{cases} \tag{4.32}$$

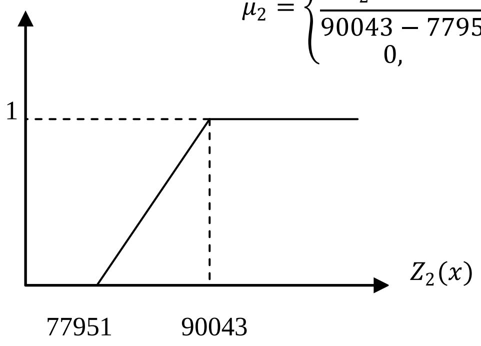



Figure 4.7 Membership function of fuzzy maximum $Z_2$ (Maximize the total coverage of collected batteries)

$\mu_{Z_3}$

$$\mu_{Z_3} = \begin{cases} 1, & if\ Z_3 \geq 207433.4 \\ \frac{Z_3 - 100390}{207433.4 - 100390}, & if\ \ 100390 \leq Z_3 \leq 207433.4 \\ 0, & if\ \ Z_3 \leq 100390 \end{cases} \tag{4.33}$$

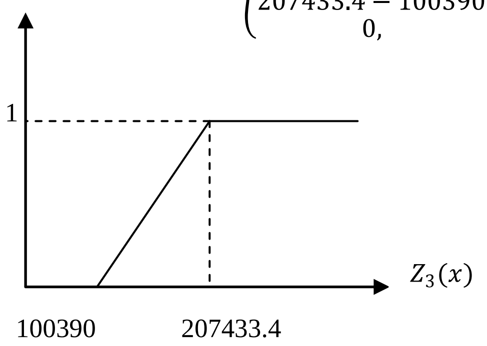



Figure 4.8 Membership function of fuzzy maximum $Z_3$ (Maximize the total volume flexibility)

### *4.6.2 Determination of Desirable Achievement Degrees Using Linguistic Evaluations in a Group Decision Making Environment*

The determination of a desirable achievement degree for a goal is a difficult and troublesome task for the decision makers (DMs) in fuzzy environment. For selecting the desirable achievement degrees imprecisely, a recommended method is to use linguistic terms such as ‘important’, somewhat important’ and ‘very important’ and so on, to verbally define the importance of each fuzzy goal (Chen and Tsai, 2001).

The linguistic term is a variable whose values are words or phrase in natural or artificial language (Jamalnia and Soukhakian, 2009). Also, according to Chang (1996), a fuzzy linguistic variable is often characterized by fuzzy numbers. In this research, for determining the desirable achievement degrees of the objectives precisely and dealing with the imprecise or vague nature of linguistic assessment, Liou and Wang (1992) approach for ranking fuzzy numbers is used in group decision making environment where the weights/importance and index of optimism of each group member are different.

Before applying this method, L = {VLI, LI, SLI, M, SHI, HI, VHI} is defined as a set of linguistic values about the importance of different goals where VLI = very low important, LI = low important, SLI = somewhat low important, M = medium, SHI = somewhat high important, HI = high important, VHI = very high important.

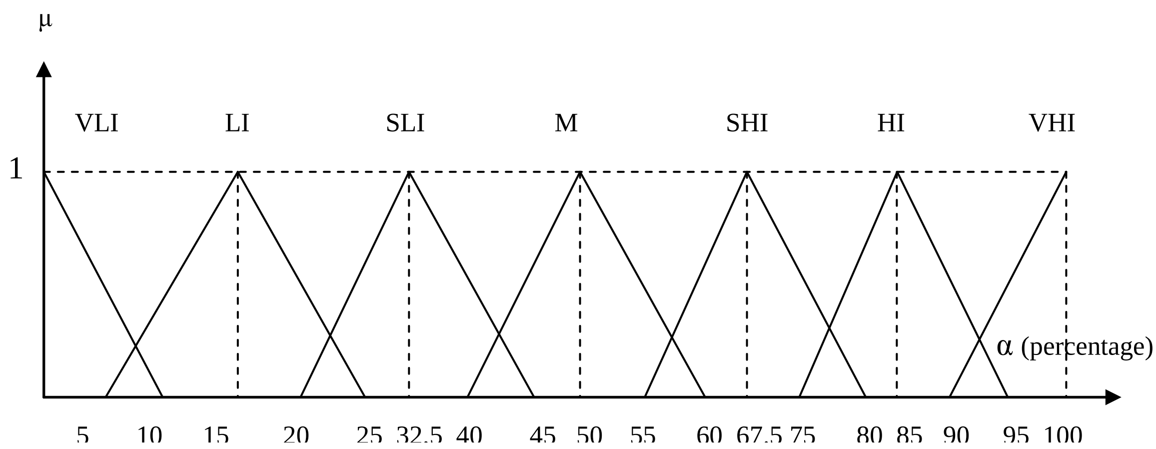



Figure 4.9 Membership functions for linguistic terms (Belmokaddem et al., 2009)

Figure 4.9 shows the membership functions for linguistic values about the importance of different objectives. Where $\mu_L(\alpha)$ represents the membership functions of each linguistic values, $\mu_L(\alpha) \in [0,1]$ and $\alpha$ shows the variable taking an achievement degree in the interval of $[\alpha_{min}, \alpha_{max}]$, $0 \leq \alpha_{min} \leq \alpha_{max} \leq 1$. These linguistic values about the importance of different goals and DMs are characterized by triangular fuzzy numbers as given in Table 4.8.

Table 4.8 Linguistic variables for the importance/weight of different goals and DMs (Jamalnia and Soukhakian, 2009)

| Linguistic variables | Triangular fuzzy numbers |
|---|---|
| Very low important (VLI) | (0,0,%10) |
| Low important (LI) | (%5,%15,%25) |
| Somewhat low important (SLI) | (%20,%32.5,%45) |
| Medium (M) | (%40,%50,%60) |
| Somewhat high important (SHI) | (%55,%67.5,%80) |
| High important (HI) | (%75,%85,%95) |
| Very high important (VHI) | (%90,%100,%100) |

In the approach of Liou and Wang (1992), where given $\alpha \in [0,1]$ and represents the index of optimism in order to reflect the decision maker's optimistic attitude, total integral value of the triangular fuzzy number $\tilde{A} = (a, b, c)$ can be calculated as follows (Kaptanoglu and Ozok, 2006):

$$I_T^{\alpha} = \frac{1}{2}\alpha(b + c) + \frac{1}{2}(1 - \alpha)(a + b)$$

$$I_T^{\alpha} = \frac{1}{2}[\alpha c + b + (1 - \alpha)a] \tag{4.34}$$

When $\alpha = 0$, total integral value represents a pessimistic decision maker and is calculated through equation (4.35).

$$I_T^{0}(\tilde{A}) = \frac{1}{2}[b + a] \tag{4.35}$$

When $\alpha = 0.5$, total integral value represents a moderate decision maker and is calculated through equation (4.36).

$$I_T^{0.5}(\tilde{A}) = \frac{1}{2}[0.5c + b + 0.5a] \quad (4.36)$$

When $\alpha = 1$, total integral value represents an optimistic decision maker and is calculated through equation (4.37).

$$I_T^{1}(\tilde{A}) = \frac{1}{2}[c + b] \quad (4.37)$$

We can use $I_T^{\alpha}(\tilde{A}) = \alpha_k$ as the desired achievement degree of the $k^{\text{th}}$ fuzzy goal. In this study, the computational procedure of Chang's (1996) extent fuzzy AHP was used for determining the weights of the group members.

The fuzzy AHP method is a well known tool for multi-criteria decision making (MCDM) problem in the literature. Since the conventional methods are inadequate for dealing with the imprecise or vague nature of linguistic assessment, one of the most commonly used tool in MCDM environment, fuzzy analytic hierarchy process (AHP) is used to determine the importance weights of the DMs. Because, according to Chen, Tzeng, and Ding (2008), real world decision problems involve complexity and uncertainty. Therefore, DMs may be more reluctant to provide crisp judgments than fuzzy ones.

Furthermore, fuzzy approaches allow for more accurate description of the human judgments based on the human perception. In literature, there are a lot of different studies including fuzzy-AHP applications. For instance, Karimi et al. (2011) used fuzzy TOPSIS and fuzzy-AHP methods to select the most appropriate wastewater treatment process. In their study, technical, economical, environmental, administrative criteria and their sub-criteria were weighted and then evaluation of these criteria and rankig of the alternatives have been done by fuzzy TOPSIS and fuzzy-AHP methods using triangular fuzzy numbers. Kahraman, Cebeci, and Ulukan

(2003) used fuzzy-AHP method for supplier selection problem of a white good manufacturer in Turkey. Kong and Liu (2005) applied fuzzy-AHP method to determine the key factors that affect the performance or success of e-commerce. They determined the trust, system quality, content quality, online service and use as the best success factors.

The computational procedure of Chang's (1996) extent fuzzy-AHP is described as follows:

**Step 1:** The value of the fuzzy synthetic extent with respect to the *i*-th object is defined by:

$$S_i = \sum_{j}^{m} M_{g_i}^{j} \otimes \left[ \sum_{i}^{n} \sum_{j}^{m} M_{g_i}^{j} \right]^{-1} \qquad (4.38)$$

Where all the $M_{g_i}^{j}$ (j = 1,2,.... m) are triangular fuzzy numbers.

**Step 2:** As $M_1 = (l_1, m_1, u_1)$ and $M_2 = (l2, m_2, u_2)$ are two triangular fuzzy numbers, the degree of possibility of $M_2 \geq M_1$ is defined by:

$$V(M_2 \geq M_1) = \begin{cases} 1, & if\ m_2 \geq m_1 \\ 0, & if\ l_1 \geq u_2 \\ \dfrac{l_1 - u_2}{(m_2 - u_2) - (m_1 - l_1)}, & otherwise \end{cases} \qquad (4.39)$$

**Step 3:** To compare $M_1$ and $M_2$, we need both the values of $V(M_1 \geq M_2)$ and $V(M_2 \geq M_1)$. The degree possibility for a convex fuzzy number to be greater than $k$ convex fuzzy numbers $M_i$ ($i=1,2,..k$) can be defined by:

$$V(M \geq M_1, M_2, \dots\dots.. M_k) = V[(M \geq M_1)\ and\ (M \geq M_2)\ and\ \dots.and\ (M \geq M_k)]$$
$$= min V(M \geq M_i), i = 1,2, \dots\dots k \qquad (4.40)$$

Assume that $d'(A_i) = min\, V(S_i \geq S_k)\ \ for\ k = 1,2, \ldots \ldots n; k \neq i$ then the weight vector is given by:

$$W' = (d'(A_1), d'(A_2), \ldots \ldots ., d'(A_n))^T \qquad (4.41)$$

Where $A_i$ ($i=1,2, \ldots n$) are $n$ elements.

**Step 4:** Via normalization, the normalized weight vectors are:

$$W = (d(A_1), d(A_2), \ldots \ldots ., d(A_n))^T \qquad (4.42)$$

Where, $W$ is a non-fuzzy number.

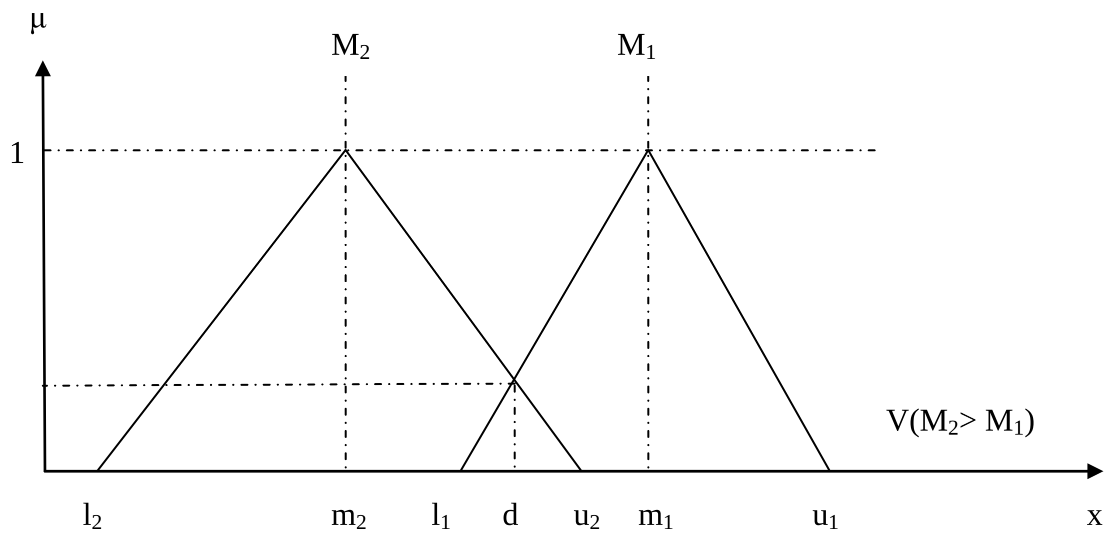



Figure 4.10 The intersection between $M_1$ and $M_2$ (Ozdagoglu, 2007; Zhu, Jing, and Chang, 1999)

According to the figure 4.10, $V(M_1 \geq M_2) = 1 \quad if\ m_1 \geq m_2,$

$$V(M_1 \geq M_2) = hgt(M_1 \cap M_2) = \mu_{M_1}(d) \qquad (4.43)$$

Where $d$ is the ordinate of the highest intersection point $d$ between $\mu_{M_1}$ and $\mu_{M_2}$. The ordinate of the highest intersection point D is given by equation (4.44):

$$V(M_2 \geq M_1) = hgt(M_1 \cap M_2) = \frac{l_1 - u_2}{(m_2 - u_2) - (m_1 - l_1)} \quad (4.44)$$

A pair-wise matrix for assigning the weights of each group member is given in the following Table 4.9.

Table 4.9 Pair-wise comparison for the weights of the DMs in the group decision making

| | **DM 1** | **DM 2** | **DM 3** |
|---|---|---|---|
| **DM 1** | M | HI | SHI |
| **DM 2** | LI | M | SLI |
| **DM 3** | SLI | SHI | M |

Then the fuzzy evaluation matrix in Table 4.10 which is composed of triangular fuzzy numbers can be derived by using Table 4.8.

Table 4.10 Fuzzy evaluation matrix for the DMs

| | **DM 1** | **DM 2** | **DM 3** |
|---|---|---|---|
| **DM 1** | (0.4,0.5,0.6) | (0.75,0.85,0.95) | (0.55,0.675,0.8) |
| **DM 2** | (0.05,0.15,0.25) | (0.4,0.5,0.6) | (0.2,0.325,0.45) |
| **DM 3** | (0.2,0.325,0.45) | (0.55,0.675,0.8) | (0.4,0.5,0.6) |

The value of the fuzzy synthetic extent is calculated as follows:

$$S_{Z_1} = (1.7, 2.025, 2.35) \otimes \left(\frac{1}{5.5}, \frac{1}{4.5}, \frac{1}{3.5}\right) = (0.309, 0.45, 0.671)$$

$$S_{Z_2} = (0.65, 0.975, 1.3) \otimes \left(\frac{1}{5.5}, \frac{1}{4.5}, \frac{1}{3.5}\right) = (0.118, 0.216, 0.371)$$

$$S_{Z_3} = (1.15, 1.5, 1.85) \otimes \left(\frac{1}{5.5}, \frac{1}{4.5}, \frac{1}{3.5}\right) = (0.209, 0.333, 0.529)$$

These fuzzy values should be compared.

$$V\left(S_{Z_1} \geq S_{Z_2}\right) = 1, \qquad V\left(S_{Z_1} \geq S_{Z_3}\right) = 1$$

$$V\left(S_{Z_2} \geq S_{Z_1}\right) = 0.209, \qquad V\left(S_{Z_2} \geq S_{Z_3}\right) = 0.581$$

$$V\left(S_{Z_3} \geq S_{Z_1}\right) = 0.653, \qquad V\left(S_{Z_3} \geq S_{Z_2}\right) = 1$$

Then, priority weights are calculated as follows:

$d'(Z_1) = \min(1, 1) = 1$
$d'(Z_2) = \min(0.209, 0.581) = 0.209$
$d'(Z_3) = \min(0.653, 1) = 0.653$

Priority weights form $W'$= (1, 0.209, 0.653) vector. After normalization of these values, normalized weight vectors are calculated as *W*= (0.54, 0.11, 0.35). Therefore, weights of the three decision makers in group decision making process are obtained based on fuzzy-AHP method. In this research, importance of the objectives is evaluated by the three decision makers which have different index of optimism as seen in Table 4.11.

Table 4.11 Evaluations of the relative importance of the objectives by DMs

| | **DM 1 (Moderate)** | **DM 2 (Optimistic)** | **DM 3 (Pessimistic)** |
|---|---|---|---|
| **Total CLSC costs** | HI | VHI | HI |
| **Total coverage** | HI | SHI | SHI |
| **Total volume flexibility** | M | SHI | SLI |

Obtaining desirable achievement degree for each fuzzy goal in a group decision making environment can be achieved in five steps:

1. Determine the weights/importance of each group member.
2. Specify the index of optimism of each group member.
3. Obtain the linguistic assessment of each fuzzy goal from the DMs.
4. Calculate the individual desirable achievement degree of each goal for each DM according to his/her index of optimism.
5. Then, calculate the overall priority of each fuzzy goal by using equation (4.45) based on the weighted geometric mean.

$$\overline{\alpha_k} = \left(\prod_{i=1}^{n} {\alpha_{ik}}^{w_i}\right)^{1/\sum_{i=1}^{n} w_i} \tag{4.45}$$

Where $\overline{\alpha_k}$ is overall priority of the $k^{th}$ fuzzy goal, $\alpha_{ik}$ is the individual desirable achievement degree of $i^{th}$ DM for $k^{th}$ fuzzy goal and $w_i$ is weight of the $i^{th}$ DM. Overall priorities are obtained by using the above procedure as in the Table 4.12.

Table 4.12 Overall priorities for determination of desirable achievement degrees

| | **DM 1 (Moderate-0.54)** | **DM 2 (Optimistic-0.11)** | **DM 3 (Pessimistic-0.35)** | **Overall Priority** |
|---|---|---|---|---|
| **Total CLSC cost** | (0.75,0.85,0.95) $\alpha_{11}$=0.85 | (0.9,1.0,1.0) $\alpha_{21}$=1.0 | (0.75,0.85,0.95) $\alpha_{31}$=0.8 | 0.847 |
| **Total coverage** | (0.75,0.85,0.95) $\alpha_{12}$=0.85 | (0.55,0.675,0.8) $\alpha_{22}$=0.7375 | (0.55,0.675,0.8) $\alpha_{32}$=0.6125 | 0.746 |
| **Total volume flexibility** | (0.4,0.5,0.6) $\alpha_{13}$=0.5 | (0.55,0.675,0.8) $\alpha_{23}$=0.7375 | (0.2,0.325,0.45) $\alpha_{33}$=0.2625 | 0.416 |

Therefore, desirable achievement degrees are determined in a group decision making environment where the decision makers have different weights and index of optimisms as 0.847, 0.746 and 0.416 based on Liou and Wang's approach (1992) for ranking fuzzy numbers.

### *4.6.3 Transformation of FMOLP Problem to Equivalent Crisp Model*

The proposed FMOLP model is converted to the equivalent LP model as in (Chen and Tsai, 2001) with one objective function that maximizes the summation of achievement degrees of fuzzy goals. In the crisp model, $\mu_{Z_k} \geq \alpha_k$ was added for all $k$ goals to the system constraints. Where $\alpha_k$ is the desired achievement degree of $k^{th}$ goal. Desirable achievement degrees can be defined as the importance of the fuzzy goals. Therefore, more important goals have higher achievement degrees (Chen and Tsai, 2001). Also, the membership functions of the fuzzy objectives $\mu_{Z_k}$ are known. The transformation of the fuzzy optimization problem that is proposed earlier in section 4.4.5 into the equivalent crisp model can be made as follows:

$$Maximize\ f(\mu) = \sum_{k=1}^{3} \mu_k \tag{4.46}$$

$$\mu_1 \leq \frac{15374000 - Z_1}{3872698} \tag{4.47}$$

$$\mu_2 \leq \frac{Z_2 - 77951}{12092} \tag{4.48}$$

$$\mu_3 \leq \frac{Z_3 - 100390}{107043} \tag{4.49}$$

$Constraint\ set\ from\ (4.4)\ to\ (4.26)$

$$\mu_1 \geq 0.847 \tag{4.50}$$

$$\mu_2 \geq 0.746 \tag{4.51}$$

$$\mu_3 \geq 0.416 \tag{4.52}$$

$$w_j, c_j, h_j, r_l, y_{jk}, y1_{kj}, y_{bj}, y1_{bj} \ \in (0,1) \tag{4.53}$$

$$x_{bijk}, x1_{bkjl}, q_{bj}, q1_{bj} \ \geq 0\ and\ integer\ and\ \ all\ other\ variables\ are\ continuous \tag{4.54}$$

$$\mu_1, \mu_2, \mu_3 \geq 0 \tag{4.55}$$

Flow chart associated with application of the method is indicated in Figure 4.11.

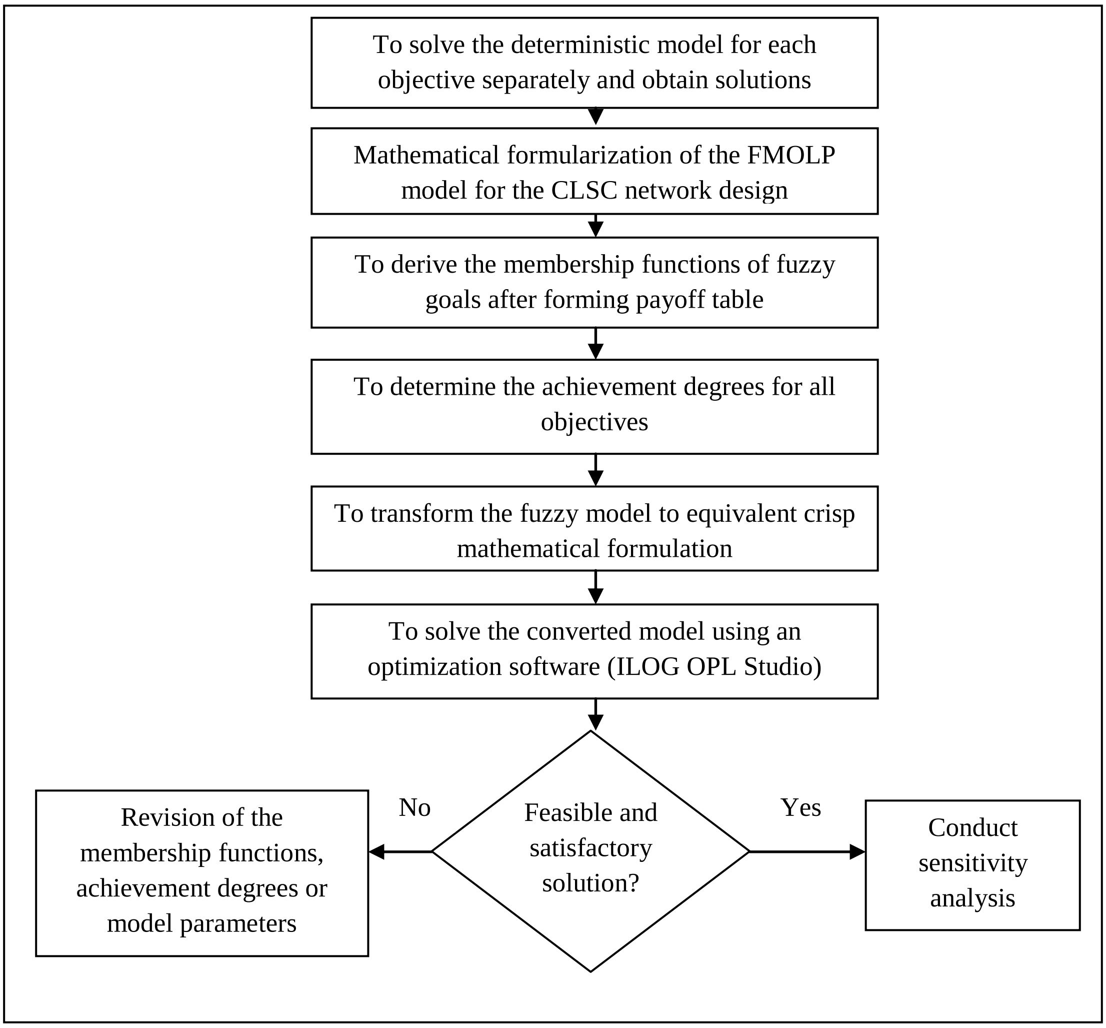



Figure 4.11 Flow chart for solution procedure of the FGP-DIP for CLSC network design

### *4.6.4 Fuzzy Optimization Results of the Case Study*

Using ILOG OPL Studio version 6.3 modelling language, the equivalent crisp model yields the following fuzzy optimization results, optimal network structure and optimal production-recycling plan as it seen from Tables 4.13, 4.14 and 4.15, Figure 4.12.

Table 4.13 Results of the fuzzy optimization

| **Total cost** | **Total coverage** | **Total volume flexibility** | **CPU time** | **Total number of variables-constraints** | **Satisfaction degrees** | | |
|---|---|---|---|---|---|---|---|
| | | | | | $\mu_1$ | $\mu_2$ | $\mu_3$ |
| $11963000 | 87808 units | 178210 units | 12.33 sec. | 5745-6189 | 0.88 | 0.82 | 0.73 |

According to the results obtained from the efficient compromise solution that is provided with the satisfaction of multiple fuzzy goals, six of the regional wholesalers, none of the hybrid facilities, five of collection centres and two of the licensed recycling facilities should be opened at the candidate or potential locations.

Total revenue obtained from the used battery sales is equal to zero. This means no spent battery sales to the scrap dealers are available. Instead of selling of used batteries from the hybrid facilities or collection centres to the scrap dealers, purchasing of them are more advantageous when considering the three objectives simultaneously.

Amounts of purchased used batteries by the collection centres from the scrap dealers and then sent to the opened recycling facility are given as follows:

- For the used battery type-1, 8063, 8503, 9095, 3943 and 8630 units of spent battery are purchased by the collection centres (second, third, sixth, ninth and tenth depots), respectively.

- For the used battery type-2, 8097, 5227, 9999 and 3160 units of spent battery are purchased by the collection centres (second, third, ninth and tenth depots), respectively.
- For the used battery type-3, 568 and 2800 units of spent battery are purchased by the collection centres (second and ninth depots), respectively.

Optimal production/recycling quantities of each battery type at each new battery manufacturer and opened recycling facility are given in Table 4.14. Furthermore, transportation quantities of recycled materials/components in kilograms from the licensed recycling facilities to the new battery manufacturers are given in Table 4.15.

Table 4.14 Optimal production-recycling quantities

| **Battery manufacturer-1** | | | **Battery manufacturer-2** | | | **Recycling facility-1** | | | **Recycling facility-2** | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| T-1 | T-2 | T-3 | T-1 | T-2 | T-3 | T-1 | T-2 | T-3 | T-1 | T-2 | T-3 |
| 35000 | 28000 | 41560 | 1600 | 15050 | 0 | 57868 | 29365 | 38238 | 0 | 18514 | 0.9 |

Table 4.15 Amounts of recycled materials transported from licensed recycling facilities to manufacturers

| **Recycling facility/manufacturer** | **New battery manufacturer-1** | | | **New battery manufacturer-2** | | |
|---|---|---|---|---|---|---|
| Material/component type | Type-1 | Type-2 | Type-3 | Type-1 | Type-2 | Type-3 |
| Licensed recycling facility-1 | 1106600 | 535920 | 264680 | - | 12006 | - |
| Licensed recycling facility-2 | - | - | - | 149700 | 68045 | 40825 |

In addition, amounts of purchased materials/components by the new battery manufacturers from the different vendors are given as follows:

- 50000 kg of component type-1 is purchased by new battery manufacturer-1 from the vendor-1.
- 60000 kg of component type-1 is purchased by new battery manufacturer-1 from the vendor-2.
- 42943 kg of component type-1 is purchased by new battery manufacturer-1 from the vendor-3.

- 27056 kg of component type-1 is purchased by new battery manufacturer-2 from the vendor-3.

Therefore, first new battery manufacturer meets most of its component/material requirements via recycling option since the first potential recycling facility is opened next to it. As it is seen from the Figure 4.12, spent battery returns are not available from the all dealers or retailers since the used batteries can be collected from only covered dealers or retailers by the opened hybrid facilities/collection centres according to the maximum acceptable service distance determined earlier.

Most of the collected spent batteries are shipped to the opened recycling facility-1, only the third and ninth collection centres sent the used batteries to the licensed recycling facility-2. In addition, the licensed recycling facility-1 sent the recycled component to both manufacturer-1 and 2. However, licensed recycling facility-2 sent the all recycled components only to the battery manufacturer-2.

### 4.7 Sensitivity Analysis

In order to investigate the sensitivity of the model and analyzing the sensitivity of decision parameters regarding collection-recovery system to variation of satisfaction degrees related to the each fuzzy goal, the proposed FMOLP problem is resolved with different values of return rate (%), maximum number of opened facilities for the spent battery collection, recycling capacities of licensed recycling facilities, respectively.

In the first scenario, low, medium and high rates of returns of each battery type are considered. In the second scenario, variation on the satisfaction degrees of each fuzzy goal is analyzed by changing the maximum number of opened facilities for used battery returns (such as numbers of opened collection centres and hybrid facilities). Analyzing the sensitivity by changing capacities of licensed recycling facilities is performed in scenario 3. Sensitivity analysis is applied in three scenarios using application data as seen in Table 4.16.

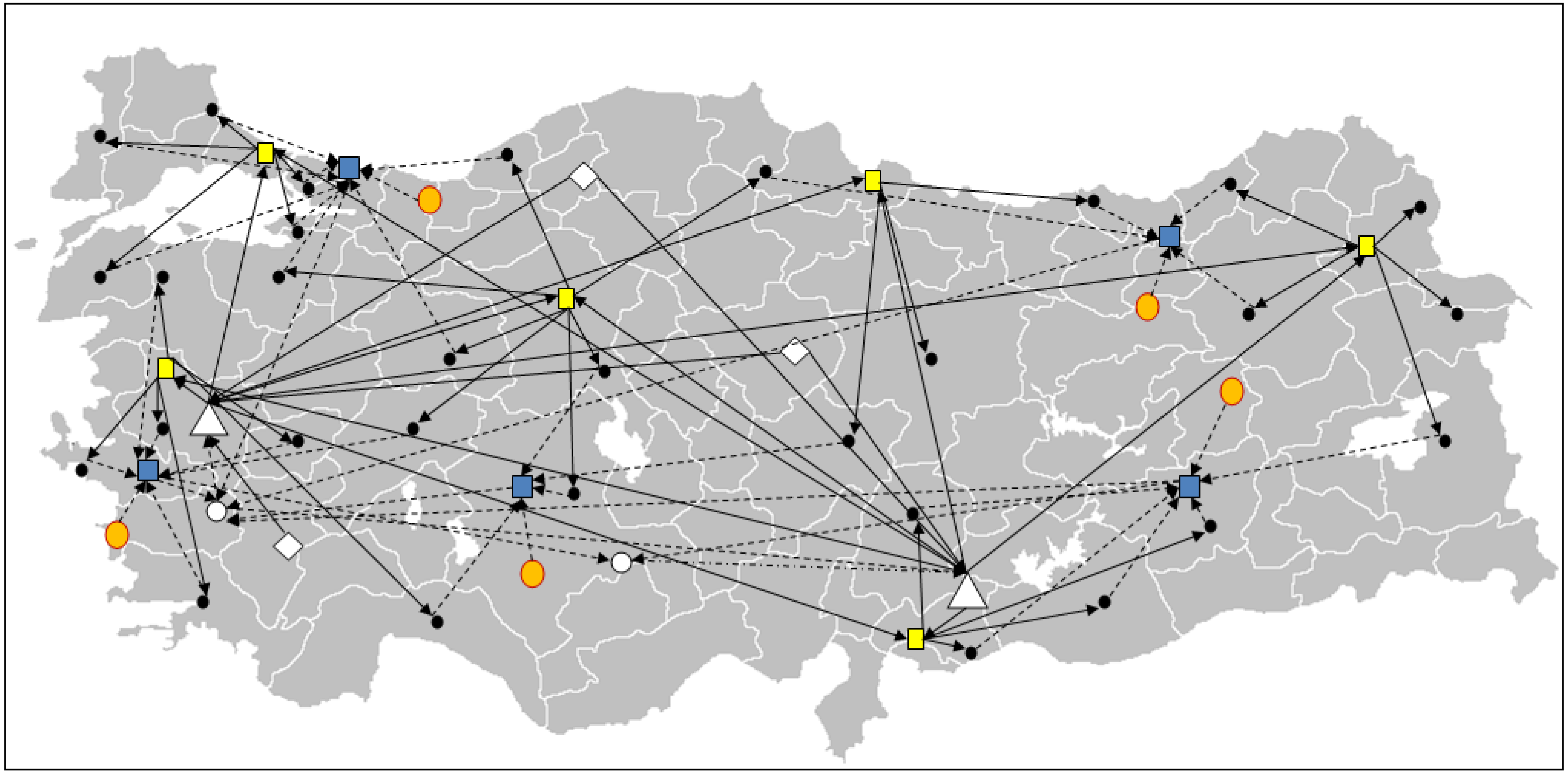


Figure 4.12 Optimal forward and reverse network structure considering all objectives simultaneously in the fuzzy environment

Table 4.16 Application data of three scenarios

| **Scenario** | **Item** | **Run 1** | **Run 2** | **Run 3** |
|---|---|---|---|---|
| Scenario 1 | $S_b$ | Low (%40) | Medium (%60) | High (%90) |
| Scenario 2 | $N$ | 4 | 5 | 6 |
| Scenario 3 | $REcap_{bl}$ | 3000 | 6000 | 15000 |

Since the max-min limits of the fuzzy goals will change in each run of the scenarios, membership functions should be revised for each run of each scenario before applying the scenarios. For instance, limit values of the objectives are modified for each run of the scenario 1 as given Table 4.17 below. Similarly, membership functions should be reconstructed for each run of the other two scenarios.

Table 4.17 Limits of the objectives for each run in scenario 1

| **Objectives** | **Run 1** | | **Run 2** | | **Run 3** | |
|---|---|---|---|---|---|---|
| | Lower bound | Upper bound | Lower bound | Upper bound | Lower bound | Upper bound |
| Total CLSC costs | $13034392 | $15451000 | $11849152 | $15228000 | $11423061 | $15474000 |
| Total coverage | 43912 units | 45144 units | 56448 units | 67716 units | 72243 units | 101574 units |
| Total volume flexibility | 171020 units | 200091 units | 99596 units | 205735 units | 100580 units | 207433 units |

Application of the three scenarios in the equivalent crisp formulation of the proposed model yield the following satisfaction degrees for each fuzzy goal as given in Figures 4.13, 4.14 and 4.15.

In the first scenario, different return rates of spent batteries are taken into account. According to Figure 4.13, higher return rates provide lower or equal costs, higher amounts of spent battery collection (coverage) and higher volume flexibility for the CLSC.

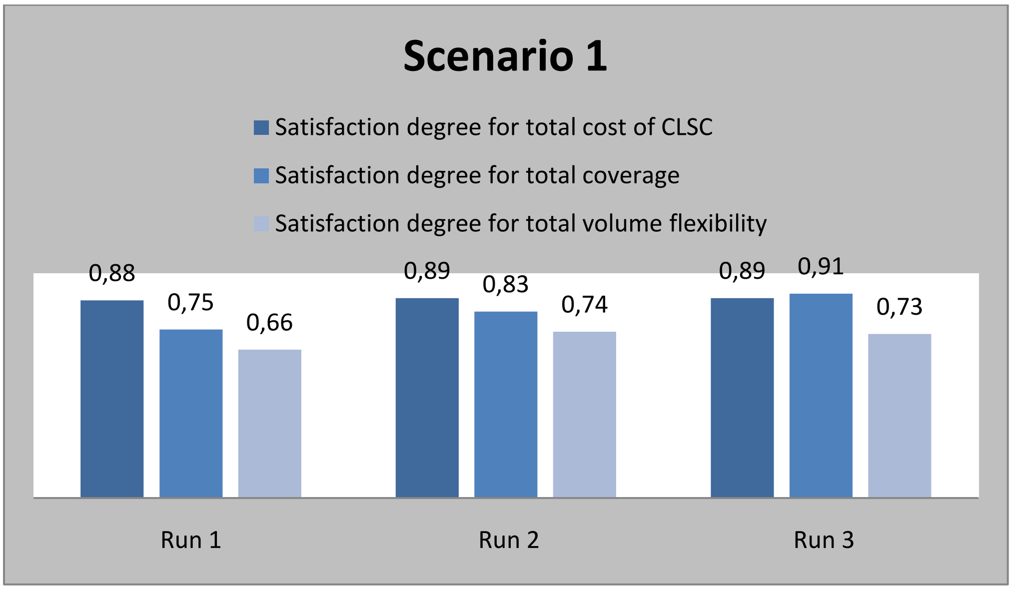



Figure 4.13 Satisfaction degrees as results of the scenario 1

In the second scenario, effects of the maximum number of opened facilities (collection centres and hybrid facilities) for used battery returns are examined. According to Figure 4.14, when the maximum number of opened facilities is increased, total coverage and total volume flexibility will also increase. In addition, satisfaction degree for the total cost will not decline too much due to set up one more collection centre or hybrid facility.

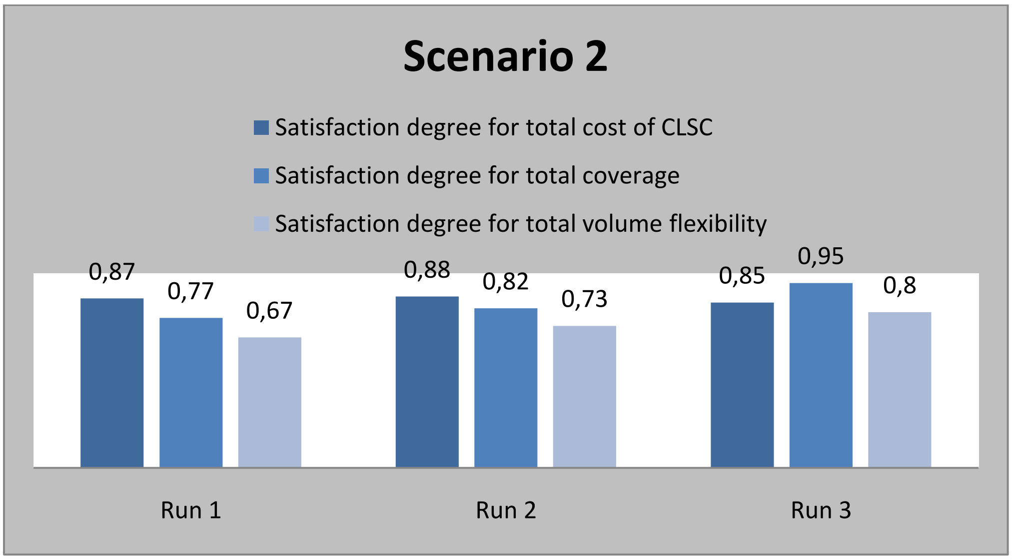



Figure 4.14 Satisfaction degrees as results of the scenario 2

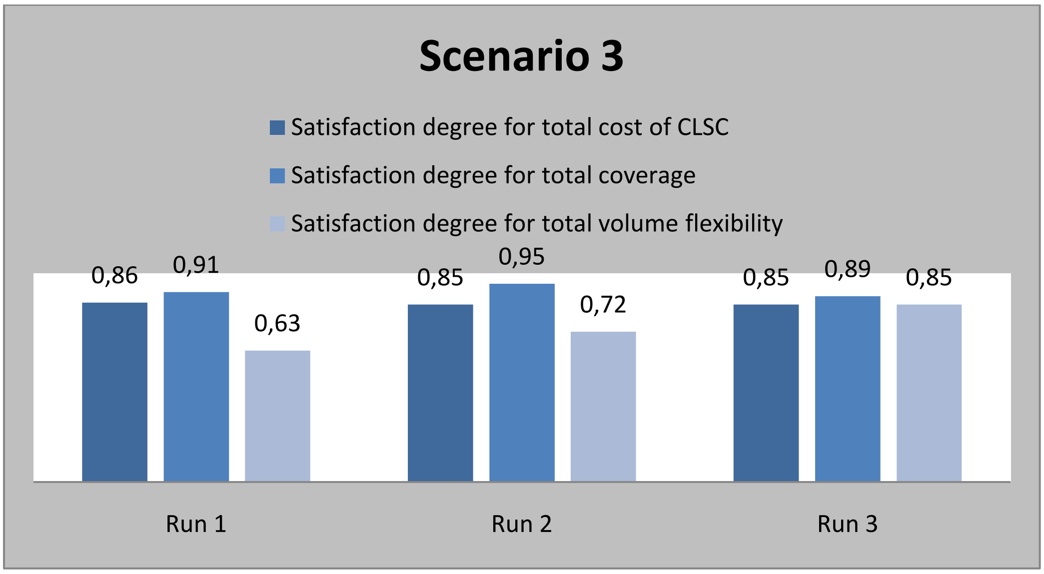



Figure 4.15 Satisfaction degrees as results of the scenario 3

Scenario 3 shows that recycling capacity of the licensed recycling facilities has not an important impact on the total cost. On the other hand, increasing in recycling capacity up to a specified level will improve the satisfaction degree of total coverage. In addition, since the recycling flexibility will grow in case of capacity increases, satisfaction degree for total volume flexibility always increases.

### 4.8 Chapter Conclusion and Future Researches

In this Chapter, a mixed integer linear programming model with fuzzy objectives is developed for a multi-objective, multi-echelon and multi-product CLSC in lead/ acid battery industry. The proposed model attempts to minimize the total costs of the CLSC, to maximize the collection of returned batteries through the opened collection centers or hybrid facilities and finally to maximize the total volume flexibility which consists of manufacturing/recycling volume flexibility and distribution/collection volume flexibility.

For solving the proposed fuzzy multi-objective optimization model, a fuzzy goal programming approach with different goal priorities is used. Determination of the desirable achievement degrees of all fuzzy goals (which is seen as a difficult task in the literature) is achieved by a new approach in a group decision making environment where the importance and optimism characteristics of the group members are different.

At the end of the Chapter, the proposed model is validated by a case study which is inspired from the real life battery recovery system in Turkey. In addition, sensitivity analysis is conducted by using different scenarios regarding the collection-recovery system such as return rate, recycling capacity etc. Development of a heuristic solution approach for larger size problems is scheduled as a future work. Furthermore, an extended mathematical model may be developed by adding multi-period, multi-mode transportation in network design.

# CHAPTER FIVE
# DESIGNING ENVIRONMENTALLY CONSCIOUS TIRE CLOSED-LOOP SUPPLY CHAIN NETWORK WITH MULTIPLE RECOVERY OPTIONS VIA MULTI-OBJECTIVE MATHEMATICAL PROGRAMMING

## 5.1 Introduction

Significant environmental problems have been experienced due to the growth in the amount of used tires every year. For instance, more than one billion brand new tires are manufactured by approximately 500 producers all over the world. Likewise, nearly one billion of scrap tires are disposed every year which cause health hazard and environmental problems. However, the chemicals leached from the old tires are hazardous for human health, water and air pollution (Hubpages, n.d.). Since these high amounts of used tires are disposed all over the world via the traditional methods that are no friends to the environment, several recovery alternatives have become vital issues for the last decade. In fact, both remanufacturing and recycling options for end of life tires have becoming crucial issues nowadays because of the difficulty related to the dissociation of these scrap tires in the environment and the economic benefits of material and energy recovery.

In this respect, effective collection, storage, recycle and proper disposal of these end of life tires without damaging the environment require designing an efficient CLSC network. Furthermore, managing the end-of-life tires effectively and balancing the forward and reverse flows in a value chain are challenging tasks in the tire industry. Thus, designing an economically and ecologically optimized CLSC network is a prerequisite for tire producers so as to accomplish their increased environmental responsibility and sustainable development.

Based on this motivation, this Chapter presents the examination of different recovery options such as remanufacturing, recycling and energy recovery simultaneously and states a holistic modeling approach via mixed integer linear programming to manage the integrated tire management system and recover the value in the scrap tire.

Our model aims to maximize the total CLSC profit and minimize the total environmental impact along the CLSC. Most of the available papers in the literature which investigate the optimal tire supply chain configuration are only cost or profit oriented. There are limited numbers of studies which emphasize the environmental perspectives in CLSCs based on life cycle assessment analysis (LCA).

For instance, Sasikumar, Kannan, and Haq (2010) formulated a mixed integer non-linear programming model for maximizing the profit of a multi-echelon, multi-period RL network with a real life case of truck tire retreading. They only taken into account the remanufacturing option in their model.

In the sustainable recovery network model of Dehghanian and Mansour (2009) only scrap tires' processing in plants and energy recovery in cement plants were considered.

Lebreton and Tuma (2006) developed a mathematical model for assessing the profitability of tire remanufacturing case. Return probability and quality levels were also taken into account in their model.

Subulan and Tasan (2011b) proposed a profit oriented mixed integer linear programming model for a tire CLSC with multiple recovery options and time periods.

Since the lack of environmental considerations in CLSCs network modeling, we applied eco-indicator 99 methodology to quantify the environmental impact throughout the tire CLSC. This method incorporates the quantitative LCA in order to formulate the appropriate environmental measure objective to guide strategic decision making in supply chains (Goedkoop and Spriensma, 2000). It is highlighted that eco-indicator 99 methodology has more advantages over other methods since it adopts a systematic way to perform the subjective procedure regarding assigning and scoring of the relative importance to different impact categories (Hugo and Pistikopoulos, 2005). In addition, this method yields the assessment of environmental impact related to a product or manufacturing process by using a single indicator/index (Dehghanian and Mansour, 2009). So, this method found wide practical applications especially in designing chemical supply chains. Moreover, Coca-Cola Hellenic calculates its ecological footprint throughout the value chain by utilizing eco-indicator 99 method (Coca-Cola Hellenic, 2010).

The main purpose of this research is to develop a multi-objective, multi-echelon, multi-product and multi-period network design model for a tire CLSC with multiple recovery options and green image.

## 5.2 Chapter Outline

The rest of this Chapter is organized as follows. In section 5.3, the relevant literature on applications of eco-indicator 99 method in supply chain design and planning are given. In section 5.4, details of the problem with the model formulation, assumptions and model parameters are described. Then in section 5.5, application of the proposed model to an illustrative example inspired by Turkey case is discussed. This section also involves the detailed explanations related to the solution methodology, interactive fuzzy goal programming. In section 5.6, evaluation of the computational results through Taguchi experimental design method is performed. In section 5.7, Chapter conclusion and suggestions for future researches are given, respectively.

## 5.3 A Review of Eco-Indicator 99 Methodology Applications in Supply Chain Network Design and Planning

Eco-indicator 99 methodology is a damage modeling and life cycle assessment based method which is applied for quantification and estimation of environmental impacts of a process or product. The main three damage categories involved in eco-indicator 99 method are (1) human health, (2) eco-system quality and (3) resource depletion (Goedkoop and Spriensma, 2000; Pishvaee and Razmi, 2012). These damage categories can be divided into 11 different sub-categories as in Figure 5.1 (Barba-Gutiérrez, Adenso-Díaz, and Hopp, 2008; Hofstetter, 1998).

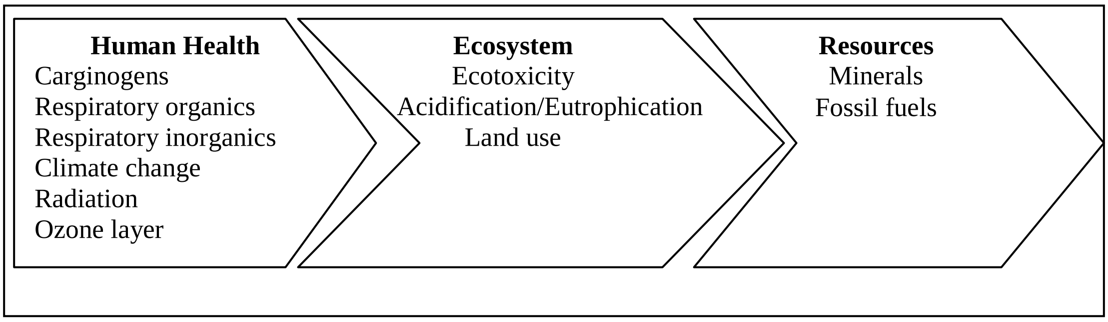



Figure 5.1 Eco-indicator 99 impact categories

Five application steps of eco-indicator 99 methodology are given as follows (Goedkoop and Spriensma, 2000) and tracked in section 5.4.2 for tire case in detail.

(i) definition of system boundary, functional unit and purpose of the eco-indicator calculation,
(ii) description of life cycle stages,
(iii) quantification of materials and processes,
(iv) forming and filling the form,
(v) interpretation of the results.

There are limited numbers of papers in the literature that present the application of eco-indicator 99 methodology while designing and planning of a supply chain network. Some of the papers are reviewed as follows:

A mathematical programming based model for the strategic investment planning of a chemical supply chain is proposed by Hugo and Pistikopoulos (2003). They tried to achieve minimum environmental damage by using eco-indicator 99 methodology and maximum net present value in their model. The outcomes of that model are selection of the most appropriate technologies and related production profiles over time, allocation of technologies to the potential plants, assignment of the products produced by the opened plants to meet the demands at markets.

In their extended model (Hugo and Pistikopoulos, 2005) they added the capacity planning strategy (capacity expansion policy) and gave the comprehensive version of their model structure. In the solution phase, they reformulated the proposed multi-objective optimization problem as a multi-parametric mixed integer linear programming model in order to obtain Pareto optimal solution set.

Michelsen (2006) used eco-indicator 99 method to evaluate the environmental performance of products for redesigning the extended supply chain problem in furniture production case.

A three objective mathematical model is developed by Dehghanian and Mansour (2009) for designing a sustainable recovery network of scrap tires. The objectives were maximization of total net profits of processing the end of life tires, minimization of the total environmental impact and maximization of social benefits. Environmental impacts are calculated using eco-indicator method and social impact of each recovery option is evaluated by “analytical hierarchy process” methodology. For providing the Pareto-optimal solution set for network configuration, they applied the multi-objective genetic algorithm.

A generic recovery network model which aims to maximize profit and minimize eco-indicator score is proposed by Duque, Barbosa-Póvoa, and Novais (2009) for optimal design and operations of industrial polluted waste. They proved that acceptable environmental performance can be obtained and close-to green scenarios can be reached with very small profit losses. In addition by performing sensitivity analysis, it is concluded that variation of different damage weights (human health, ecosystem quality and natural resources) have not very significant effect on the damage function.

Extensive version of their paper is presented in (Duque, Barbosa-Póvoa, and Novais, 2010). In that study, eco-indicator 99 methodology is incorporated into a mixed integer linear programming model for design and planning of industrial networks. For modeling this industrial network, maximal state task network representation is used. The goals of that study are maximization of profit and minimization eco-indicator 99 score. Multi-objective analysis is also performed via an approximation to the Pareto curve which is obtained by applying ε-constraint method.

A bi-criterion stochastic non-convex mixed-integer non-linear programming model is developed by Gosalbez and Grossmann (2010) for optimal design and planning of a sustainable chemical supply chain. Environmental damage is accounted by eco-indicator 99 method while taking into account the uncertainty in the parameters of environmental damage model (uncertainty of damage factors). The objectives of that study were maximization of net present value and minimization of environmental impact. For globally optimizing the proposed non-convex model, a novel spatial branch and bound algorithm with sets up connections between global optimization and multi-objective optimization was developed.

Varela, Barbosa- Póvoa, and Novais (2011a) incorporated three methodologies namely: resource-task-network, eco-indicator 99 and goal programming approach. They modeled the supply chain network design and planning problem via a resource-task-network methodology, accounted the environmental impacts through the balanced conflicting objectives by using goal programming.

Varela, Barbosa- Póvoa, and Novais (2011b) also developed a mixed integer symmetric fuzzy linear programming model for planning and design of a supply chain taking simultaneously into account both economic and environmental aspects. They assumed that environmental impacts are generated only by electricity and diesel consumption. Proposed model provides the decisions related to installation of technological resources and their capacities, selection of technological processes and supply chain topology. For the solution, fuzzy-like approach is used to deal with the uncertain multi-objective nature.

Pishvaee and Razmi (2012) proposed a multi-objective fuzzy mathematical programming model for designing an environmental CLSC. They considered the customer demand, cost items and capacities as uncertain parameters and presented them by fuzzy numbers defined by their possibility distribution. They used eco-indicator 99 method to quantify the environmental impact and applied two-phase approach for solving the proposed multi-objective possibilistic mixed integer programming model. In the first phase, the model is converted into an equivalent auxiliary crisp model, then interactive fuzzy solution approach based on ε-constraint method is applied to find the final preferred compromise solution.

### 5.4 Problem Description and Model Development

In the forward supply chain of the problem, different types of brand new tires are transported to the distribution centers to meet the tire dealers' demands. Also, retreaded tires are shipped from the several retreading companies to distribution centers to meet the secondary market requirements. Storage of the both newly produced and retreaded tires are allowed in the distribution centers.

In the reverse supply chain, a certain percentage of used tires are collected from the end users at their end of life while the end users replace it by a new one in the tire dealer. On the other hand, there are reverse flows of used tires through initial collection centers. All of the returned tires are inspected, consolidated and sorted for different recovery alternatives at the centralized return points. Used tires which are in appropriate condition for retreading process are transported to retreading companies directly and the remaining scrap tires can be evaluated by different alternatives such as energy recovery, material recycling, land filling and incineration according to their conditions.

These alternative ways are elaborated and discussed in section 5.4.1 from the technical point of view.

There are two different options for the new tire plants to supply materials such as rubber, steel and fiber. One is purchasing them from the external suppliers and the other one is acquiring them by recycling way from the tire recycling facilities. In addition, tire granulate which composes of an important part of the recycled materials can be reused in third party applications such as road paving (ground applications), sport fields, roofing materials, footwear, automobile parts, etc. (Panagiotidou and Tagaras, 2005). The configuration of the system which is just discussed can be portrayed as shown in Figure 5.2.

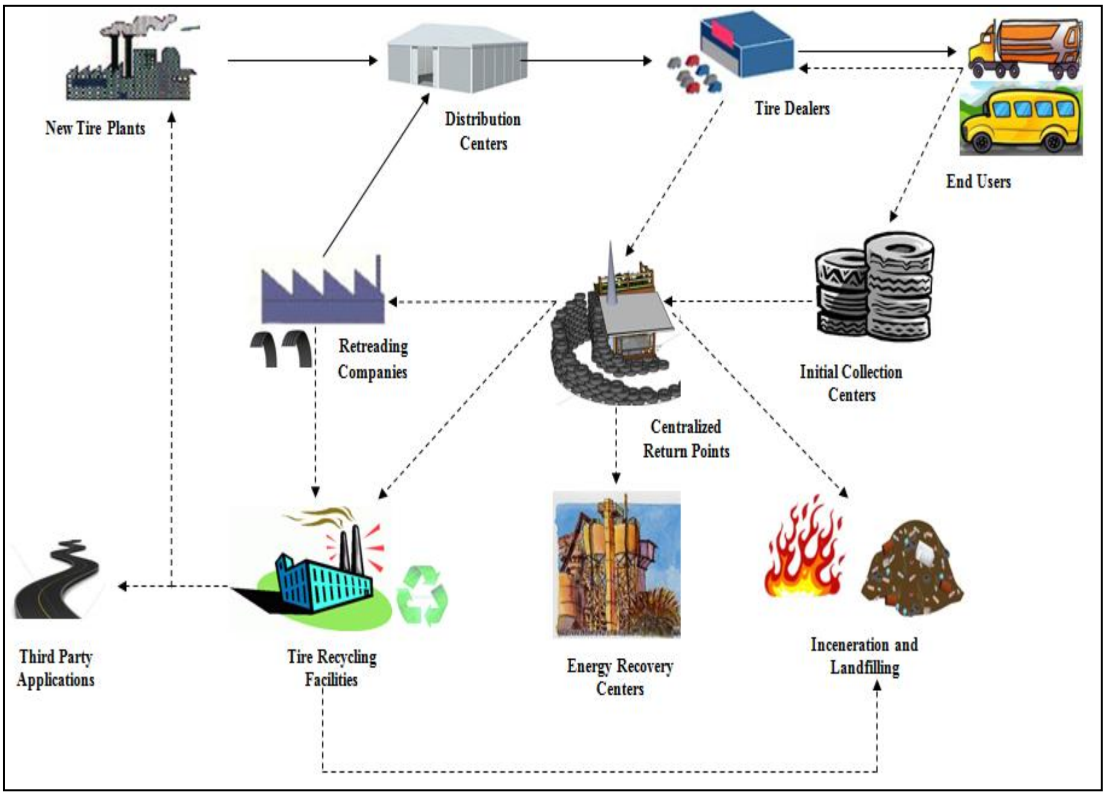



Figure 5.2 Closed-loop supply chain network representation with multiple recovery options for end-of-life tires

### *5.4.1 Different Recovery Options for End-of-Life Tires*

Scrap tires can in principle be used in five alternative ways: direct reuse, retreading, recycling, energy recovery and disposal (land filling or incineration) as shown in Figure 5.3 These alternatives are explained briefly as follows:

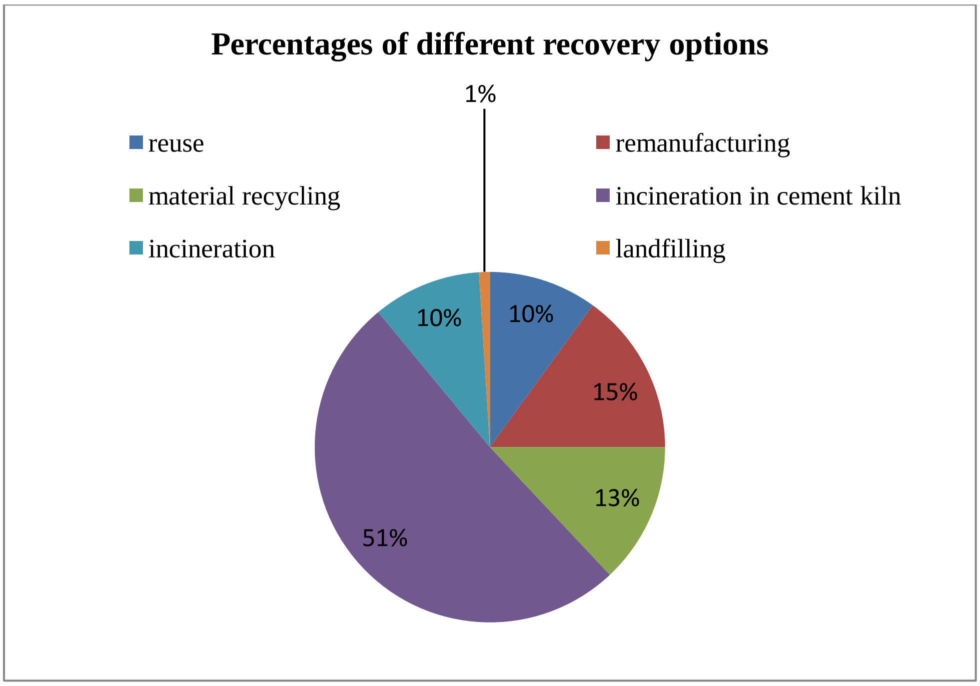



Figure 5.3 Different recovery alternatives for used tires and related percentages (Institut für Energie und Umweltforschung [IFEU], 1999)

- **Direct reuse**

Direct reuse is the most environmental friendly alternative from all viewpoints. However, a small fraction of the used tires can be resold in the secondary markets, typically in developing countries (Panagiotidou and Tagaras, 2005; Patentdocs, n.d.).

- **Retreading**

A tire consists of a tread and a casing as seen in Figure 5.4. As a result of a specified using period of a tire, the tread become useless. On the other hand, the casing may be available for reusing. So, tire retreading can be performed and defined as "process of replacing the worn rubber, outer layer of a tire, with a new rubber layer". Retreading process provides saving up to %80 of the material cost of a tire (Debo and Wassenhove, 2005). Material resource conservation and $CO_2$ emissions reduction that are generated during production processes are noted as major environmental contributions of tire retreading process (Bridgestone, n.d.). Although, the retreaded tires produce almost the same mileage as compared with newly produced tires, they are sold for %30 to %50 discounts in the secondary markets (Lebreton and Tuma, 2006; Sasikumar, Kannan, and Haq, 2010).

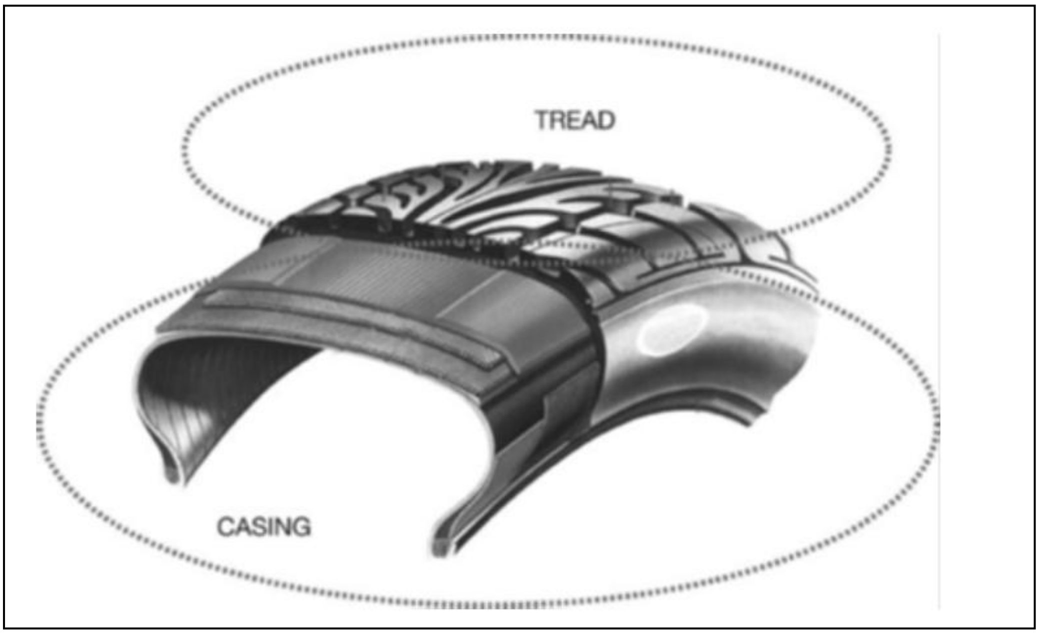



Figure 5.4 Structure of a tire (Lebreton, 2007)

- **Recycling**

Tire recycling means material recovery from the shredded tires or granulate (Panagiotidou and Tagaras, 2005). Rubber powder, steel wires and fibers are all separated in the material recycling phase and tire granulate can be reused in upper asphalt layer of roads and other several applications as mentioned earlier. In contrast to these third party applications, reusing tire rubber or granulate for its originally intended purpose is the most preferred alternative since it's environmentally and economically benefits (waterworld, n.d.). Ferrao, Ribeiro, and Silva (2008) also emphasized that tire recycling has an environmental benefit since avoiding the production of certain materials from the primary sources.

- **Energy recovery**

Since tires have a high energy content compared to other types of solid waste and fossil fuel, they can be used for electricity generation by incineration and as a fuel substitute in thermoelectric plants and cement kilns and paper mills. Moreover, this fuel has a low cost in comparison with classical fuels (Bridgestone Europe, 2009). Therefore, energy may be recovered by various types of incineration and energy reclaiming can be yielded through this recovery option (Lebreton and Tuma, 2006; Panagiotidou and Tagaras, 2005; Sasikumar, Kannan, and Haq, 2010).

- **Disposal**

Land filling is the least preferred option for the waste management of scrap tires. Because, when land filled, tires must first be quartered, split or shredded to reduce the potential for the tires to resurface (Environmental Fact Sheet, 2011). Shredding the tire avoids the above problems but requires high processing costs. Moreover, scrap tires occupy large amounts of landfill space and remain intact for a long time (Ferrao, Ribeiro, and Silva, 2008). Some other difficulties associated with the tire land filling can be summarized by (infohouse, n.d.) as follows:

(i) tires tend to float or rise in a landfill and come to the surface,
(ii) the void space provides potential sites for the harboring of rodents,
(iii) landfilling has also a negative impact on the diminishing underground supplies of fresh water (envirotire, n.d.).

Incineration of whole tires in industrial furnaces is environmentally safe when we compare it with the uncontrolled tire fires since they cause air and ground pollution dramatically (waterworld, n.d.). The main problems of incinerating the scrap tires are highlighted by Sharma et al. (2000) as follows:

(i) shortage of incineration technology,

(ii) production of soot through the imperfect burning of waste tires,

(iii) production of toxic gases such as $SO_2$, CO, $H_2S$ etc. when tires are burnt.

Except the reusing, all of the recovery options discussed above are taken into account in our developed mathematical model for more realistic reflection of the real world applications.

### *5.4.2 Application of Eco-Indicator 99 Method in a Tire CLSC*

In order to evaluate the potential environmental impacts during the entire life stages, LCA are conducted in a tire CLSC using eco-indicator 99 methodology in this section. Besides forming a profit oriented CLSC configuration, provision of environmental improvements in a tire CLSC network is the main purpose of the eco-indicator calculation in this Chapter.

The boundary of the examined system is the integrated CLSC network depicted in Figure 5.2. A schematic overview of a tire's life cycle is defined based on (Best Foot Forward, 2008; Bridgestone, n.d.; Japan India Trade Associates, n.d.; Kazakhstan rubber recycling, n.d.; maxxis, n.d.; waterworld, n.d.) as shown in Figure 5.5. In this general process tree, quantification of materials and processes along the life cycle are also involved. Generally the life cycle stages of a tire involve: (i) raw material acquisition phase, (ii) production phase, (iii) distribution/transportation phase, (iv) use phase, (v) end-of-life collection phase, (vi) end-of-life processing phase, (vii) energy recovery phase, (viii) remanufacturing phase, (ix) recycling phase, (x) warehousing/storage phase and (xi) disposal phase. However, usage of tires by the end users are disregarded in the eco-indicator calculation since it has no impact on the decisions of the proposed mathematical model.

After the definition of the life cycle, a form that includes the standard relevant indicator values and related amounts of each phase will be prepared and filled up calculated scores for each phase by multiplying the amounts by the indicator values.

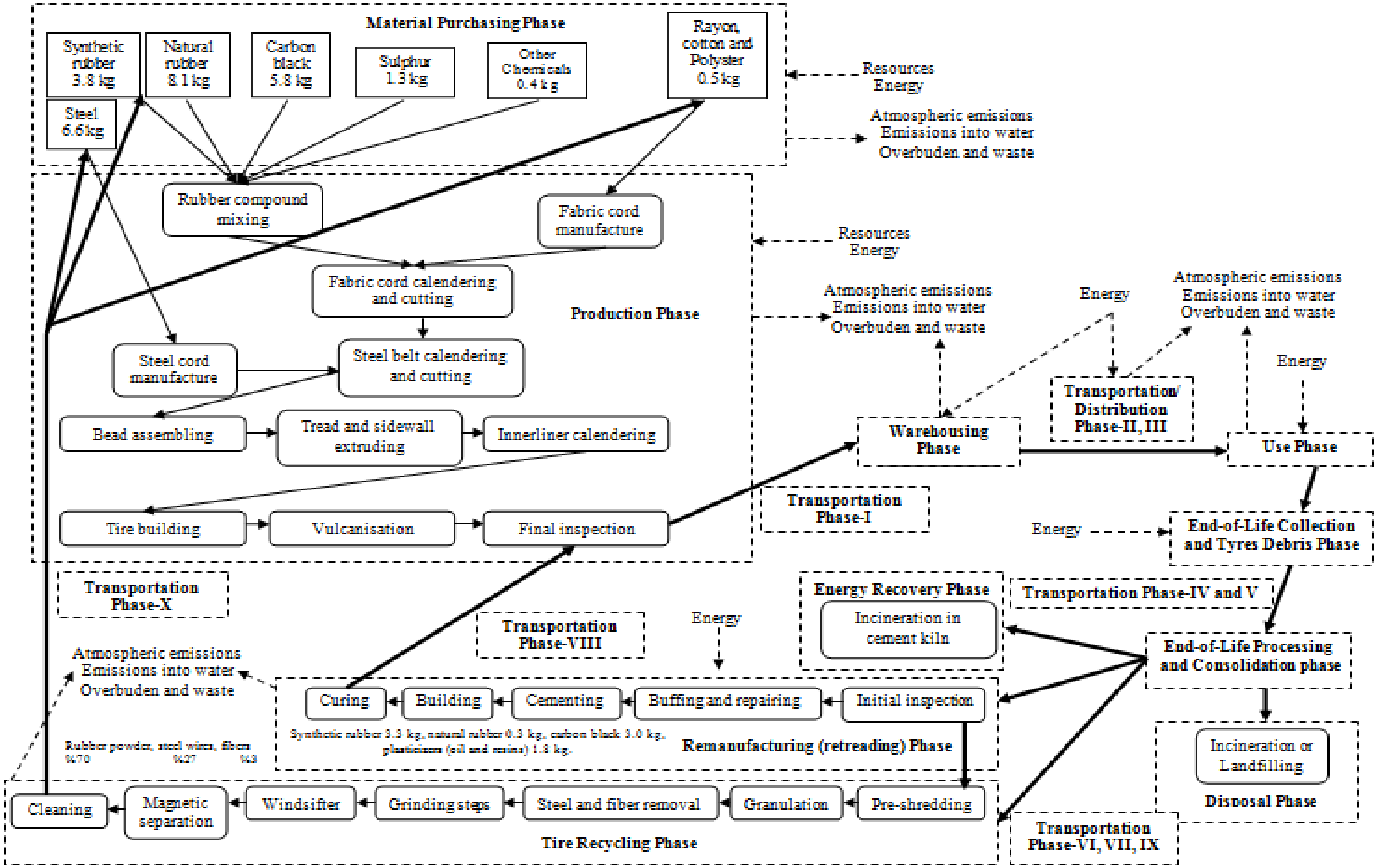



Figure 5.5 LCA boundries and process tree of a tire throughout the different life cycle phases

Then, subsidiary results are added together. Thereafter, total milli-points which represent the total environmental impact for each phase are obtained. The indicator values, amounts and overall results represent the environmental parameters as inputs in the proposed model whereas the related decision quantities for each phase reflect the decisions variables as outputs obtained from the solution of the model. The prepared partially completed form for a 17.5 truck tire is depicted in following Table 5.1.

Table 5.1 Partially completed form for LCA of a 17.5 truck tire

| | |
|---|---|
| **Product or component:** 17.5 Truck tires | **Project:** Closed-loop supply chain network design: Environmental impact assessment |
| **Date:** 20.03.2012 | **Author:** Subulan K. |
| **Notes and conclusions:** | |

| **Material purchasing** | | | |
|---|---|---|---|
| **Material and acquisition type** | **amount** | **indicator** | **result** |
| Rubber purchased by an external supplier | | | |
| Rubber powder obtained through recycling | | | |
| Steel purchased by an external supplier | | | |
| Steel wires obtained through recycling | | | |
| Textiles purchased by an external supplier | | | |
| Fibers obtained through recycling | | | |
| **Total [mPt]** | | | |

| **Production** (Materials, processing, transport and extra energy) | | | |
|---|---|---|---|
| **material or process** | **amount** | **indicator** | **result** |
| Synthetic rubber | 3.8 kg | | |
| Natural rubber | 8.1 kg | | |
| Sulphur | 1.3 kg | | |
| Rayon, cotton and polyster | 0.5 kg | | |
| Steel | 6.6 kg | | |
| Carbon black | 5.8 kg | | |
| Other chemicals | 0.4 kg | | |
| Rubber compound mixing | | | |

Table 5.1 Partially completed form for LCA of a 17.5 truck tire (Continues)

| | | | |
|---|---|---|---|
| Steel cord manufacture | | | |
| Fabric cord calendering and cutting | | | |
| Steel belt calendering and cutting | | | |
| Bead assembling | | | |
| Tread and sidewall extruding | | | |
| Innerliner calendering | | | |
| Tire building | | | |
| Vulcanisation | | | |
| Final inspection | | | |
| **Total [mPt]** | | | |
| **Environmental protection technology factor** | **Overall results** | | |
| Buiding technology type-1 | | | |
| Buiding technology type-2 | | | |
| Buiding technology type-3 | | | |

| **Distribution/Transportation** (Transport processes of newly manufactured, retreaded and scrap tires also recycled materials) – (in millipoints per tkm) | | | |
|---|---|---|---|
| **transport vehicle** | **amount* distance** | **indicator** | **result** |
| Truck 16t | | 34 | |
| Truck 28t | | 22 | |
| Truck 40t | | 15 | |
| **Total [mPt]** | | | |

| **Warehousing** (proportional to the volume capacity of the distribution centers and centralized return points) | | | |
|---|---|---|---|
| **module type** | **capacities of the modules** | **indicator** | **result** |
| Module q=1 for distribution centers | | | |
| Module q=1 for centralized return points | | | |
| Module q=2 for distribution centers | | | |
| Module q=2 for centralized return points | | | |
| Module q=3 for distribution centers | | | |
| Module q=3 for centralized return points | | | |
| **Total [mPt]** | | | |

Table 5.1 Partially completed form for LCA of a 17.5 truck tire (Continues)

| **Collection** (end-of-life collection and tyres debris) | | | |
|---|---|---|---|
| **Collection route** | **amount** | **indicator** | **result** |
| Collection by tire dealers | | | |
| Collection by initial collection centers | | | |
| **Total [mPt]** | | | |

| **End of life processing** (except warehousing) | | | |
|---|---|---|---|
| **process** | **amount** | **indicator** | **result** |
| Inspection and sorting for different recovery alternatives | | | |
| Cleaning | | | |
| Consolidation processes | | | |
| **Total [mPt]** | | | |

| **Remanufacturing (retreading)** (Materials, processing, transport and extra energy) | | | |
|---|---|---|---|
| **material or process** | **amount** | **indicator** | **result** |
| Synthetic rubber | 3.3 kg | | |
| Natural rubber | 0.3 kg | | |
| Carbon black | 3.0 kg | | |
| Plasticizers (oil and resins) | 1.8 kg | | |
| Initial inspection | | | |
| Buffing and repairing | | | |
| Cementing | | | |
| Building | | | |
| Curing | | | |
| Final inspection | | | |
| **Total [mPt]** | | | |
| **Environmental protection technology factor** | **Overall results** | | |
| Buiding technology type-1 | | | |
| Buiding technology type-2 | | | |
| Buiding technology type-3 | | | |

Table 5.1 Partially completed form for LCA of a 17.5 truck tire (Continues)

| **Energy recovery** | | | |
|---|---|---|---|
| **process** | **amount** | **indicator** | **result** |
| Incineration in cement kiln or thermoelectric plants | | | |
| **Total [mPt]** | | | |

| **Recycling** (processing, transport and extra energy) | | | |
|---|---|---|---|
| **material or process** | **amount** | **indicator** | **result** |
| Pre-shredding | | | |
| Granulation | | | |
| Steel and fiber removal | | | |
| Grinding steps | | | |
| Windsifter | | | |
| Magnetic separation | | | |
| Cleaning | | | |
| **Total [mPt]** | | | |
| **Environmental protection technology factor** | **Overall results** | | |
| Buiding technology type-1 | | | |
| Buiding technology type-2 | | | |
| Buiding technology type-3 | | | |

| **Disposal (**disposal processes) | | | |
|---|---|---|---|
| **type of processing** | **amount** | **indicator** | **result** |
| Incineration scarp tires | | | |
| Landfill scrap tires | | | |
| **Total [mPt]** | | | |

When we look at the comparison of each phase in terms of environmental impact from the previous studies, it is concluded by Ferrao, Ribeiro, and Silva (2008) and PRé Consultants (2001) that other than use phase, production and landfill phases have the greatest impact. On the other hand, energy recovery phase, retreading phase and recycling phase yield negative figures. In other words, environmental profit is gained during these phases.

### *5.4.3 Model Assumptions*

Some of the assumptions included in this Chapter are as follows:

- Shortages or backordering are not allowable.
- Except the fixed set-up costs for the opened facilities, cost parameters at all stages of the CLSC network do not change throughout the time periods.
- Transportation lead times between the stages are not taken into account.
- The tire dealers' demands for brand new and retreaded tires are assumed to be known and deterministic.
- Quantity of returned tires from a given tire dealer is the fraction of total demand of that dealer.
- Amounts of used tires returned through the initial collection centers in each time period are also known and deterministic.
- It is assumed that the selling price for brand new tires is cheaper when the end users leave their used tires at the tire dealer.
- Only one environmental protection technology can be chosen by each new tire plant, retreading company and recycling facility. Advanced environmental protection technologies have more installation costs but have less environmental impact.
- Modular capacities are only available for opened distribution centers and centralized return points. Other facilities have capacitated nature.
- Only the truck and bus tires can be retreaded. So, all demand data for retreaded passenger car tires are taken as zero.
- All of the initial inventory levels at the new tire plants, distribution centers and centralized return points are assumed to be zero.
- Specific disposal ratios are accepted for incineration and land filling.
- Aspiration levels of the goals are assumed to be uncertain and stated as fuzzy.

### *5.4.4 Notation*

#### *5.4.4.1 Indices and Sets*

| | |
|---|---|
| $p$ | set of brand new tire types or family (car, truck and bus), $p=1, \ldots, P$ |
| $p'$ | set of retreaded tire types or family (car, truck and bus), $p'=1, \ldots, P'$ |
| $c$ | set of material or component type (steel, rubber and fiber), $c=1,\ldots C$ |
| $i$ | set of new tire plants, $i=1,\ldots I$ |
| $d$ | set of potential locations for distribution centers, $d=1,\ldots D$ |
| $r$ | set of tire dealers, $r=1,\ldots,R$ |
| $j$ | set of initial collection centers, $j=1,\ldots J$ |
| $k$ | set of potential locations for centralized return points, $k=1,\ldots,K$ |
| $l$ | set of potential locations for retreading companies, $l=1,\ldots L$ |
| $n$ | set of potential locations for tire recycling facilities, $n=1,\ldots N$ |
| $w$ | set of cement kilns, thermoelectric plants or paper mills, $w=1,\ldots W$ |
| $b$ | set of environmental protection technologies, $b=1,\ldots B$ |
| $q$ | set of capacities of the modules, $q=1,\ldots Q$ |
| $v$ | set of vehicle types, $v=1,\ldots V$ |
| $t$ | set of time periods in planning horizon, $t=1,\ldots T$ |

#### *5.4.4.2 Parameters*

| | |
|---|---|
| $SL1_p$ | discount unit selling price of the brand new tire type $p$ to a tire dealer in the case of any tire returns |
| $SL2_p$ | unit selling price of the brand new tire type $p$ to a tire dealer without any tire returns |
| $SL3_{p'}$ | unit selling price of the retreaded tire type $p'$ to a tire dealer for secondary markets |
| $SL4_p$ | unit selling price of scrap tire type $p$ to the cement or thermoelectric plants |
| $SL5_c$ | unit selling price of recycled material type $c$ to external facilities for third party applications |
| $F1_{lt}$ | fixed set-up cost of the retreading company $l$ in the beginning of period $t$ |

$F2_{dt}$ fixed set-up cost of the distribution center *d* in the beginning of period *t*

$F3_{kt}$ fixed set-up cost of the centralized return point *k* in the beginning of period *t*

$F4_{nt}$ fixed set-up cost of the tire recycling facility *n* in the beginning of period *t*

$OC1_l$ quarterly rental and operating cost of retreading company *l*

$OC2_d$ quarterly rental and operating cost of distribution center *d*

$OC3_k$ quarterly rental and operating cost of centralized return point *k*

$OC4_n$ quarterly rental and operating cost of tire recycling facility *n*

$PC_{pib}$ production cost of per unit of tire type *p* in new tire plant *i* with environmental protection technology *b*

$RTC_{pib}$ remanufacturing cost of per unit of used tire type *p* in retreading company *l* with environmental protection technology *b*

$RC_{pib}$ recycling cost of per unit of used tire type *p* in tire recycling facility *n* with environmental protection technology *b*

$ETC1_{ib}$ investment cost for environmental protection technology *b* in new tire plant *i*

$ETC2_{lb}$ investment cost for environmental protection technology *b* in retreading company *l*

$ETC3_{nb}$ investment cost for environmental protection technology *b* in tire recycling facility *n*

$PUC_{ci}$ purchasing cost of per kg of material type *c* for new tire plant *i*

$CC_p$ collection cost per unit of used tire type *p* through the initial collection points

$TC_{pv}$ unit transportation cost of tire type *p* per kilometer using vehicle type *v*

$TC1_{p'v}$ unit transportation cost of retreaded tire type *p'* per kilometer using vehicle type *v*

$TC2_{cv}$ unit transportation cost of material type *c* per kilometer using vehicle type *v*

$MCC1_{qd}$ installing cost of module type *q* to be added to the distribution center *d*

$MCC2_{qk}$ installing cost of module type *q* to be added to the centralized return point *k*

$IC1_{pi}$ inventory holding cost of per unit of brand new tire type *p* in new tire plant *i*

$IC2_{pd}$ inventory holding cost of per unit of brand new tire type *p* in distribution center *d*

$IC3_{p'd}$ inventory holding cost of per unit of retreaded tire type *p'* in distribution center *d*

$IC4_{pk}$ inventory holding cost of per unit of scrap tire type *p* in centralized return point *k*

$IC5_{ci}$ inventory holding cost of per kg of material *c* in new tire plant *i*

$LNFC_p$ landfill cost per unit of used tire type *p*

$INC_p$ incineration cost per unit of used tire type *p*

$EI1_c$ eco-indicator value of purchasing per kg of material type *c* from external suppliers

$EI2_c$ eco-indicator value of acquiring per kg of material type *c* through recycling

$EIP_{pib}$ eco-indicator value of producing one unit of brand new tire type *p* in new tire plant *i* with environmental protection technology *b*

$EIRM_{plb}$ eco-indicator value of remanufacturing one unit of used tire type *p* in retreading company *l* with environmental protection technology *b*

$EIRC_{pnb}$ eco-indicator value of recycling one unit of used tire type *p* in tire recycling facility *n* with environmental protection technology *b*

$EIT1_{pv}$ eco-indicator value of transporting one unit of tire type *p* per kilometre using vehicle type *v*

$EIT2_{p'v}$ eco-indicator value of transporting one unit of retreaded tire type *p'* per kilometre using vehicle type *v*

$EIT3_{cv}$ eco-indicator value of transporting per kg of material type *c* per kilometre using vehicle type *v*

$EIW1_q$ eco-indicator value for warehousing/storage activities of distribution centers with *q* type capacity module

$EIW2_q$ eco-indicator value for warehousing/storage activities of centralized return points with *q* type capacity module

$EIC1_{pv}$ eco-indicator value for collecting one unit of used tire type *p* by dealers directly from the end users and shipping it using vehicle type *v*

$EIC2_{pv}$ eco-indicator value of collecting one unit of used tire type *p* by initial collection centers and shipping it using vehicle type *v*

$EIE_{pk}$ eco-indicator value of end-of-life processing for one unit of scrap tire type *p* at centralized return point *k*

$EIR_{pw}$ eco-indicator value of incinerating one unit of used tire type *p* in cement kiln or thermoelectric plant *w*

$EII_p$ eco-indicator value of incinerating one unit of scrap tire type $p$ at disposal sites

$EIL_p$ eco-indicator value of landfilling one unit of scrap tire type $p$ at disposal sites

$DE1_{prt}$ demand of tire dealer $r$ for brand new tire type $p$ in period $t$

$DE2_{p'rt}$ demand of tire dealer $r$ for retreaded tire type $p'$ in period $t$

$RE_{pjt}$ returned volume of used tire type $p$ to the initial collection center $j$ in time period $t$

$\alpha_p$ return fraction of the demand from tire dealers for tire type $p$

$B_p$ fraction of used tire type $p$ satisfying the quality specifications for recycling process

$\theta_{pl}$ recovery fraction for used tire type $p$ at retreading company $l$

$\delta_p$ fraction of used tire type $p$ shipped from centralized return points to the disposal sites

$\varepsilon$ fraction of disposed tires through incineration

$We_p$ weight of the tire type $p$

$We1_{p'}$ weight of the retreaded tire type $p'$

$a_{cp}$ percentage of contribution of material type $c$ for the tire type $p$

$Ps1_p$ unit storage capacity consumption factor for tire type $p$

$Ps2_{p'}$ unit storage capacity consumption factor for retreaded tire type $p'$

$Cs_c$ unit storage capacity consumption factor for material/component type $c$

$Cap_{ib}$ total production capacity of new tire plant $i$ with environmental protection technology $b$

$Cap1_{lb}$ total remanufacturing capacity of retreading company $l$ with environmental protection technology $b$

$Cap2_{nb}$ total recycling capacity of tire recycling facility $n$ with environmental protection technology $b$

$TSCap_i$ total storage capacity of new tire plant $i$ at the beginning of each time period

$MICap1_q$ storage capacity of module type $q$ for distribution centers

$MICap2_q$ storage capacity of module type $q$ for centralized return points

$MHCap1_q$ inbound handling capacity of module type $q$ for distribution centers

$MHCap2_q$ inbound handling capacity of module type $q$ for centralized return points

$MT1_d$ minimum throughut needed for opening of distribution center $d$

$MT2_k$ minimum throughut needed for opening of centralized return point *k*

$MT3_l$ minimum throughut needed for opening of retreading company *l*

$MT4_n$ minimum throughut needed for opening of tire recycling facility *n*

$Vcap1_{ivt}$ total transportation capacity of vehicle type *v* from new tire plant *i* in time period *t*

$Vcap2_{dvt}$ total transportation capacity of vehicle type *v* from distribution center *d* in time period *t*

$Vcap3_{rvt}$ total transportation capacity of vehicle type *v* from tire dealer *r* in time period *t*

$Vcap4_{jvt}$ total transportation capacity of vehicle type *v* from initial collection center *j* in time period *t*

$Vcap5_{kvt}$ total transportation capacity of vehicle type *v* from centralized return point *k* in time period *t*

$Vcap6_{lvt}$ total transportation capacity of vehicle type *v* from retreading company *l* in time period *t*

$Vcap7_{nvt}$ total transportation capacity of vehicle type *v* from tire recycling facility *n* in time period *t*

$d1_{id}$ distance from new tire plant *i* to distribution center *d*

$d2_{dr}$ distance from distribution center *d* to tire dealer *r*

$d3_{rk}$ distance from tire dealer *r* to centralized return point *k*

$d4_{jk}$ distance from initial collection center *j* to centralized return point *k*

$d5_{kw}$ distance from centralized return point *k* to energy recovery centers *w*

$d6_{kn}$ distance from centralized return point *k* to tire recycling facility *n*

$d7_{kl}$ distance from centralized return point *k* to retreading company *l*

$d8_{ld}$ distance from retreading company *l* to distribution center *d*

$d9_{ln}$ distance from retreading company *l* to tire recycling facility *n*

$d10_{ni}$ distance from tire recycling facility *n* to new tire plant *i*

*5.4.4.3 Decision variables*

$$y1_{lt} \left\{ \begin{array}{l} 1, \text{ if a retreading company is opened at location } l \text{ in period } t \\ 0, \text{ otherwise} \end{array} \right\}$$

$y2_{dt}$ $\begin{cases} 1, \text{ if a distribution center is opened at location } d \text{ in period } t \\ 0, \text{ otherwise} \end{cases}$

$y3_{kt}$ $\begin{cases} 1, \text{ if a centralized return point is opened at location } k \text{ in period } t \\ 0, \text{ otherwise} \end{cases}$

$y4_{lt}$ $\begin{cases} 1, \text{ if a tire recycling facility is opened at location } n \text{ in period } t \\ 0, \text{ otherwise} \end{cases}$

$y5_{jkv}$ $\begin{cases} 1, \text{ if collection center } j \text{ is allocated to centralized return point } k \text{ with vehicle } v \\ 0, \text{ otherwise} \end{cases}$

$y6_{ib}$ $\begin{cases} 1, \text{ if environmental protection technology } b \text{ is adopted by new tire plant } i \\ 0, \text{ otherwise} \end{cases}$

$y7_{lb}$ $\begin{cases} 1, \text{ if environmental technology } b \text{ is adopted by retreading company } l \\ 0, \text{ otherwise} \end{cases}$

$y8_{nb}$ $\begin{cases} 1, \text{ if environmental protection technology } b \text{ is adopted by recycling facility } n \\ 0, \text{ otherwise} \end{cases}$

$y9_{qdt}$ $\begin{cases} 1, \text{ if module type } q \text{ is integrated to distribution center } d \text{ in period } t \\ 0, \text{ otherwise} \end{cases}$

$y10_{qkt}$ $\begin{cases} 1, \text{ if module type } q \text{ is integrated to centralized return point } k \text{ in period } t \\ 0, \text{ otherwise} \end{cases}$

$Q_{pibt}$ quantity of brand new tire type $p$ manufactured in new tire plant $i$ with environmental technology $b$ during period $t$

$RTR_{plbt}$ quantity of used tire type $p$ retreaded in retreading company $l$ with environmental technology $b$ during period $t$

$REC_{pnbt}$ quantity of used tire type $p$ recycled in tire recycling facility $n$ with environmental technology $b$ during period $t$

$Qp_{cit}$ amounts of material type $c$ purchased from an external supplier to new tire plant $i$ in time period $t$

$Qs_{cnt}$ amounts of recycled material type $c$ sold from the tire recycling facility $n$ in period $t$ for third party applications

$x1_{pidvt}$ quantity of brand new tire type $p$ shipped to distribution center $d$ from new tire plant $i$ using vehicle type $v$ in period $t$

$x2_{pdrvt}$ quantity of brand new tire type $p$ shipped to tire dealer $r$ from distribution center $d$ using vehicle type $v$ in period $t$

$x3_{p'drvt}$ quantity of retreaded tire type *p'* shipped to tire dealer *r* from distribution center *d* using vehicle type *v* in period *t*

$x4_{prkvt}$ quantity of used tire type *p* shipped to centralized return point *k* from tire dealer *r* using vehicle type *v* in period *t*

$x5_{pkwvt}$ quantity of used tire type *p* shipped to cement kiln *w* from centralized return point *k* using vehicle type *v* in period *t*

$x6_{pknvt}$ quantity of used tire type *p* shipped to tire recycling facility *n* from centralized return point *k* using vehicle type *v* in period *t*

$x7_{pklvt}$ quantity of used tire type *p* shipped to retreading company *l* from centralized return point *k* using vehicle type *v* in period *t*

$x8_{p'ldvt}$ quantity of retreaded tire type *p'* shipped to distribution center *d* from retreading company *l* using vehicle type *v* in period *t*

$x9_{plnvt}$ quantity of non-remanufacturable tire type *p* shipped to tire recycling facility *n* from retreading company *l* using vehicle type *v* in period *t*

$x10_{cnivt}$ amounts of recycled material type *c* shipped to new tire plant *i* from tire recycling facility *n* using vehicle type *v* in period *t*

$I1_{pit}$ inventory level of brand new tire type *p* at new tire plant *i* in time period *t*

$I2_{pdt}$ inventory level of brand new tire type *p* at distribution center *d* in time period *t*

$I3_{p'dt}$ inventory level of retreaded tire type *p'* at distribution center *d* in time period *t*

$I4_{pkt}$ inventory level of used tire type *p* at centralized return point *k* in time period *t*

$I5_{cit}$ inventory level of material type *c* at new tire plant *i* in time period *t*

### *5.4.5 Mathematical Programming Formulation*

Two goals of the multi-objective, multi-echelon, multi product and multi-period CLSC network design problem is modeled through the following equations by using the indices, parameters and decision variables which are defined above.

1. Maximization of the total profit of the overall CLSC network:

$$Maximize\ Total\ Profit \cong TREV - (TFC + TOP + TPRC + TRMC + TRC + TTC + TCC + TMPC + TTIC + TMCC + TIC + TDC) \quad (5.1)$$

Overall revenue of the CLSC network can be obtained by selling of brand new tires, retreaded tires, used tires for energy recovery and recycled materials for other applications.

*(i)* *Total revenue;*

$$TREV = \sum_{p}^{P}\sum_{d}^{D}\sum_{r}^{R}\sum_{v}^{V}\sum_{t}^{T} x2_{pdrvt}\,.\alpha_p.SL1_p + \sum_{p}^{P}\sum_{d}^{D}\sum_{r}^{R}\sum_{v}^{V}\sum_{t}^{T} x2_{pdrvt}\,.(1-\alpha_p).SL2_p + \sum_{p'}^{P'}\sum_{d}^{D}\sum_{r}^{R}\sum_{v}^{V}\sum_{t}^{T} x3_{p'drvt}\,.SL3_{p'} + \sum_{p}^{P}\sum_{k}^{K}\sum_{w}^{W}\sum_{v}^{V}\sum_{t}^{T} x5_{pkwvt}\,.SL4_p + \sum_{c}^{C}\sum_{n}^{N}\sum_{t}^{T} Qs_{cnt}\,.SL5_c \quad (5.2)$$

Total costs of the CLSC take root from the opening and operating of facilities, production processes, material purchasing, transportation, inventory, disposal, remanufacturing, recycling, collection, technology installation and module capacity addition.

*(i)* *Total fixed set-up and operating costs for the facilities;*

$$TFC = \sum_{l}^{L}\sum_{t}^{T} F1_{lt}.(y1_{lt} - y1_{lt-1}) + \sum_{d}^{D}\sum_{t}^{T} F2_{dt}.(y2_{dt} - y2_{dt-1}) + \sum_{k}^{K}\sum_{t}^{T} F3_{kt}.(y3_{kt} - y3_{kt-1}) + \sum_{n}^{N}\sum_{t}^{T} F4_{nt}.(y4_{nt} - y4_{nt-1}) + \sum_{l}^{L}\sum_{t}^{T} OC1_l.y1_{lt} + \sum_{d}^{D}\sum_{t}^{T} OC2_d.y2_{dt} + \sum_{k}^{K}\sum_{t}^{T} OC3_k.y3_{kt} + \sum_{n}^{N}\sum_{t}^{T} OC4_n.y4_{nt} \quad (5.3)$$

*(ii)* *Total production costs;*

$$TPRC = \sum_{p}^{P}\sum_{i}^{I}\sum_{b}^{B}\sum_{t}^{T} PC_{pib} \,.\, Q_{pibt} \tag{5.4}$$

*(iii)* *Total remanufacturing costs;*

$$TRMC = \sum_{p\neq 1}^{P}\sum_{l}^{L}\sum_{b}^{B}\sum_{t}^{T} RTC_{plb} \,.\, RTR_{plbt} \tag{5.5}$$

*(iv)* *Total recycling costs;*

$$TRC = \sum_{p}^{P}\sum_{n}^{N}\sum_{b}^{B}\sum_{t}^{T} RC_{pnb} \,.\, REC_{pnbt} \tag{5.6}$$

*(v)* *Total transportation costs between the different stages;*

$$\begin{aligned} TTC = & \sum_{p}^{P}\sum_{i}^{I}\sum_{d}^{D}\sum_{v}^{V}\sum_{t}^{T} x1_{pidvt} \,.\, TC_{pv} \,.\, d1_{id} + \sum_{p}^{P}\sum_{d}^{D}\sum_{r}^{R}\sum_{v}^{V}\sum_{t}^{T} x2_{pdrvt} \,.\, TC_{pv} \,.\, d2_{dr} + \\ & \sum_{p'}^{P'}\sum_{d}^{D}\sum_{r}^{R}\sum_{v}^{V}\sum_{t}^{T} x3_{p'drvt} \,.\, TC_{p'v} \,.\, d2_{dr} + \sum_{p}^{P}\sum_{k}^{K}\sum_{w}^{W}\sum_{v}^{V}\sum_{t}^{T} x5_{pkwvt} \,.\, TC_{pv} \,.\, d5_{km} + \\ & \sum_{p}^{P}\sum_{k}^{K}\sum_{n}^{N}\sum_{v}^{V}\sum_{t}^{T} x6_{pknvt} \,.\, TC_{pv} \,.\, d6_{kn} + \sum_{p}^{P}\sum_{k}^{K}\sum_{l}^{L}\sum_{v}^{V}\sum_{t}^{T} x7_{pklvt} \,.\, TC_{pv} \,.\, d7_{kl} + \\ & \sum_{p'}^{P'}\sum_{l}^{L}\sum_{d}^{D}\sum_{v}^{V}\sum_{t}^{T} x8_{p'ldvt} \,.\, TC_{pv} \,.\, d8_{ld} + \sum_{p}^{P}\sum_{l}^{L}\sum_{n}^{N}\sum_{v}^{V}\sum_{t}^{T} x9_{plnvt} \,.\, TC_{pv} \,.\, d9_{ln} + \\ & \sum_{c}^{C}\sum_{n}^{N}\sum_{i}^{I}\sum_{v}^{V}\sum_{t}^{T} x10_{cnivt} \,.\, TC_{cv} \,.\, d10_{ni} \end{aligned} \tag{5.7}$$

*(vi)* *Total collection costs;*

$$TCC = \sum_{p}^{P}\sum_{j}^{J}\sum_{k}^{K}\sum_{v}^{V}\sum_{t}^{T} y5_{jkv} \,.\, RE_{pjt} \,.\, (TC_{pv} + CC_{p}) \,.\, d4_{jk} +$$

$$\sum_{p}^{P}\sum_{r}^{R}\sum_{k}^{K}\sum_{v}^{V}\sum_{t}^{T} x4_{prkvt}\,.\,TC_{pv}\,.\,d3_{rk} \tag{5.8}$$

*(vii)* *Material purchasing costs;*

$$TMPC = \sum_{c}^{C}\sum_{i}^{I}\sum_{t}^{T} Qp_{cit}\,.\,PUC_{ci} \tag{5.9}$$

*(viii)* *Total costs for technology installation;*

$$TTIC = \sum_{t}^{T}\sum_{i}^{I}\sum_{b}^{B} ETC1_{ib}\,.\,y6_{ib} + \sum_{l}^{L}\sum_{b}^{B} ETC2_{lb}\,.\,y7_{lb} + \sum_{n}^{N}\sum_{b}^{B} ETC3_{nb}\,.\,y8_{nb} \tag{5.10}$$

*(ix)* *Total costs for module capacity addition;*

$$TMCC = \sum_{q}^{Q}\sum_{d}^{D}\sum_{t}^{T} MCC1_{qdt}\,.\,y9_{qdt} + \sum_{q}^{Q}\sum_{k}^{K}\sum_{t}^{T} MCC2_{qkt}\,.\,y10_{qkt} \tag{5.11}$$

*(x)* *Total inventory carrying costs;*

$$TIC = \sum_{p}^{P}\sum_{i}^{I}\sum_{t}^{T} I1_{pit}\,.\,IC1_{pi} + \sum_{p}^{P}\sum_{d}^{D}\sum_{t}^{T} I2_{pdt}\,.\,IC2_{pd} + \sum_{p'}^{P'}\sum_{d}^{D}\sum_{t}^{T} I3_{p'dt}\,.\,IC3_{p'd} + \sum_{p}^{P}\sum_{k}^{K}\sum_{t}^{T} I4_{pkt}\,.\,IC4_{pk} + \sum_{c}^{C}\sum_{i}^{I}\sum_{t}^{T} I5_{cit}\,.\,IC5_{ci} \tag{5.12}$$

*(xi)* *Total disposal costs;*

$$TDC = \sum_{p}^{P}\sum_{k}^{K}\sum_{l}^{L}\sum_{n}^{N}\sum_{v}^{V}\sum_{t}^{T} (x6_{pknvt} + x9_{plnvt}).\left(1 - B_p\right).\varepsilon.INC_p + \sum_{p}^{P}\sum_{k}^{K}\sum_{l}^{L}\sum_{n}^{N}\sum_{v}^{V}\sum_{t}^{T} (x6_{pknvt} + x9_{plnvt}).\left(1 - B_p\right).(1-\varepsilon).LNFC_p + \sum_{p}^{P}\sum_{r}^{R}\sum_{j}^{J}\sum_{k}^{K}\sum_{v}^{V}\sum_{t}^{T} (x4_{prkvt} + RE_{pjt}\,.\,y5_{jkv}).\delta.\varepsilon.INC_p +$$

$$\sum_{p}^{P}\sum_{r}^{R}\sum_{j}^{J}\sum_{k}^{K}\sum_{v}^{V}\sum_{t}^{T}(x4_{prkvt} + RE_{pjt}\,.\,y5_{jkv}).\,\delta.\,(1-\varepsilon).\,LNFC_p \quad (5.13)$$

2. Minimization of the total eco-indicator score along the CLSC:

$$Minimize\ Total\ Eco - indicator\ score \cong EIMP + EIPR + EIWH + EITR + EICL + EIEOP - EIER - EIRTR - EIREC + EIDS \quad (5.14)$$

Total eco-indicator score can be provided via the multiplication of predefined standard indicator values by related amounts for each life cycle phase. Then, all of the calculated scores should be summed for obtaining the general score. Since the indicator values are negative in remanufacturing, recycling and energy recovery phases, they should be subtracted. Total eco-indicator score for each life cycle phase of a tire can be calculated as follows:

*(i)* *<u>Total environmental impact of material purchasing phase;</u>*

$$EIM = \sum_{c}^{C}\sum_{i}^{I}\sum_{t}^{T} EI1_c.\,Qp_{cit} + \sum_{c}^{C}\sum_{n}^{I}\sum_{i}^{N}\sum_{v}^{V}\sum_{t}^{T} EI2_c.\,x10_{cnivt} \quad (5.15)$$

*(ii)* *<u>Total environmental impact of production phase;</u>*

$$EIPR = \sum_{p}^{P}\sum_{i}^{I}\sum_{b}^{B}\sum_{t}^{T} EIP_{pib}\,.\,Q_{pibt} \quad (5.16)$$

*(iii)* *<u>Total environmental impact of warehousing phase;</u>*

$$EIWH = \sum_{q}^{Q}\sum_{d}^{D}\sum_{t}^{T} EIW1_q.\,MICap1_q.\,y9_{qdt} + \sum_{q}^{Q}\sum_{d}^{D}\sum_{t}^{T} EIW2_q.\,MICap2_q.\,y10_{qkt} \quad (5.17)$$

*(iv)* *Total environmental impact of distribution/transportation phase;*

$$EITR = \sum_{p}^{P}\sum_{i}^{I}\sum_{d}^{D}\sum_{v}^{V}\sum_{t}^{T} EIT1_{pv}.x1_{pidvt}.d1_{id} + \sum_{p}^{P}\sum_{d}^{D}\sum_{r}^{R}\sum_{v}^{V}\sum_{t}^{T} EIT1_{pv}.x2_{pdrvt}.d2_{dr} +$$
$$\sum_{p'}^{P'}\sum_{d}^{D}\sum_{r}^{R}\sum_{v}^{V}\sum_{t}^{T} EIT2_{p'v}.x3_{p'drvt}.d2_{dr} + \sum_{p}^{P}\sum_{k}^{K}\sum_{w}^{W}\sum_{v}^{V}\sum_{t}^{T} EIT1_{pv}.x5_{pkwvt}.d5_{km} +$$
$$\sum_{p}^{P}\sum_{k}^{K}\sum_{n}^{N}\sum_{v}^{V}\sum_{t}^{T} EIT1_{pv}.x6_{pknvt}.d6_{kn} + \sum_{p}^{P}\sum_{k}^{K}\sum_{l}^{L}\sum_{v}^{V}\sum_{t}^{T} EIT1_{pv}.x7_{pklvt}.d7_{kl} +$$
$$\sum_{p'}^{P'}\sum_{l}^{L}\sum_{d}^{D}\sum_{v}^{V}\sum_{t}^{T} EIT2_{p'v}.x8_{p'ldvt}.d8_{ld} + \sum_{p}^{P}\sum_{l}^{L}\sum_{n}^{N}\sum_{v}^{V}\sum_{t}^{T} EIT1_{pv}.x9_{plnvt}.d9_{ln} +$$
$$\sum_{c}^{C}\sum_{n}^{N}\sum_{i}^{I}\sum_{v}^{V}\sum_{t}^{T} EIT3_{cv}.x10_{cnivt}.d10_{ni} \tag{5.18}$$

*(v)* *Total environmental impact of end-of-life collection phase;*

$$EICL = \sum_{p}^{P}\sum_{r}^{R}\sum_{k}^{K}\sum_{v}^{V}\sum_{t}^{T} EIC1_{pv}x4_{prkvt}.d3_{rk} +$$
$$\sum_{p}^{P}\sum_{j}^{J}\sum_{k}^{K}\sum_{v}^{V}\sum_{t}^{T} EIC2_{pv}.y5_{jkv}.RE_{pjt}.d4_{jk} \tag{5.19}$$

*(vi)* *Total environmental impact of end-of-life processing phase;*

$$EIEOP = \sum_{p}^{P}\sum_{r}^{R}\sum_{k}^{K}\sum_{v}^{V}\sum_{t}^{T} EIE_{pk}.x4_{prkvt} + \sum_{p}^{P}\sum_{j}^{J}\sum_{k}^{K}\sum_{v}^{V}\sum_{t}^{T} EIE_{pk}.RE_{pjt}.y5_{jkv} \tag{5.20}$$

*(vii)* *Total environmental impact of energy recovery phase;*

$$EIER = \sum_{p}^{P}\sum_{k}^{K}\sum_{w}^{W}\sum_{v}^{V}\sum_{t}^{T} EIR_{pw}.x5_{pkwvt} \tag{5.21}$$

*(viii)* *Total environmental impact of tire remanufacturing phase;*

$$EIRTR = \sum_{p\neq 1}^{P}\sum_{l}^{L}\sum_{b}^{B}\sum_{t}^{T} EIRM_{plb} \,.\, RTR_{plbt} \tag{5.22}$$

*(ix)* *Total environmental impact of tire recycling phase;*

$$EIREC = \sum_{p}^{P}\sum_{n}^{N}\sum_{b}^{B}\sum_{t}^{T} EIRC_{pnb} \,.\, REC_{pnbt} \tag{5.23}$$

*(x)* *Total environmental impact of tire disposal;*

$$\begin{aligned} EIDS = &\sum_{p}^{P}\sum_{k}^{K}\sum_{l}^{L}\sum_{n}^{N}\sum_{v}^{V}\sum_{t}^{T} EII_{p}.\,(x6_{pknvt} + x9_{plnvt}).\,(1-B_{p}).\,\varepsilon \,+ \\ &\sum_{p}^{P}\sum_{k}^{K}\sum_{l}^{L}\sum_{n}^{N}\sum_{v}^{V}\sum_{t}^{T} EILP_{p}.\,(x6_{pknvt} + x9_{plnvt}).\,(1-B_{p}).\,(1-\varepsilon) \,+ \\ &\sum_{p}^{P}\sum_{r}^{R}\sum_{j}^{J}\sum_{k}^{K}\sum_{v}^{V}\sum_{t}^{T} EII_{p}.\,(x4_{prkvt} + RE_{pjt}\,.\,y5_{jkv}).\,\delta_{p}.\,\varepsilon \,+ \\ &\sum_{p}^{P}\sum_{r}^{R}\sum_{j}^{J}\sum_{k}^{K}\sum_{v}^{V}\sum_{t}^{T} EILP_{p}.\,(x4_{prkvt} + RE_{pjt}\,.\,y5_{jkv}).\,\delta_{p}.\,(1-\varepsilon) \end{aligned} \tag{5.24}$$

The constraints included in the present sustainable CLSC network design in tire industry are expressed by Eqs. (5.25) to (5.69),

$$\sum_{p}^{P} Q_{pibt} \leq Cap_{ib}\,.\,y6_{ib} \qquad \forall i \in I, \forall b, \forall t \in T \tag{5.25}$$

$$\sum_{p>1}^{P} RTR_{plbt} \leq Cap1_{lb}\,.\,y7_{lb} \qquad \forall l \in L, \forall b, \forall t \in T \tag{5.26}$$

$$\sum_{p}^{P} REC_{pnbt} \leq Cap2_{nb}\,.\,y8_{nb} \qquad \forall n \in N, \forall b \forall t \in T \tag{5.27}$$

$$\sum_{b}^{B} y6_{ib} = 1 \qquad \forall i \in I, \forall t \in T \tag{5.28}$$

$$\sum_{b}^{B} y7_{lb} \leq y1_{lt} \qquad \forall l \in L, \forall t \in T \qquad (5.29)$$

$$\sum_{b}^{B} y8_{nb} \leq y4_{nt} \qquad \forall n \in N, \forall t \in T \qquad (5.30)$$

$$I1_{pit} = I1_{pit-1} + \sum_{b}^{B} Q_{pibt} - \sum_{d}^{D}\sum_{v}^{V} x1_{pidvt} \qquad \forall p \in P, \forall i \in I, \forall t \in T \qquad (5.31)$$

$$I5_{cit} = I5_{cit-1} + Qp_{cit} + \sum_{n}^{N}\sum_{v}^{V} x10_{cnivt} - \sum_{p}^{P}\sum_{b}^{B} Q_{pibt}\,.W_p.\,a_{cp} \qquad \forall c \in C, \forall i \in I, \forall t \in T \qquad (5.32)$$

$$I2_{pdt} = I2_{pdt-1} + \sum_{i}^{I}\sum_{v}^{V} x1_{pidvt} - \sum_{r}^{R}\sum_{v}^{V} x2_{pdrvt} \qquad \forall p \in P, \forall d \in D, \forall t \in T \qquad (5.33)$$

$$I3_{p'dt} = I3_{p'dt-1} + \sum_{l}^{L}\sum_{v}^{V} x8_{p'ldvt} - \sum_{r}^{R}\sum_{v}^{V} x3_{p'drvt} \qquad \forall p' \in P', \forall d \in D, \forall t \in T \qquad (5.34)$$

$$I4_{pkt} = I4_{pkt-1} + \sum_{r}^{R}\sum_{v}^{V} x4_{prkvt} + \sum_{j}^{J}\sum_{v}^{V} RE_{pjt}\,.y5_{jkv} - \sum_{w}^{W}\sum_{v}^{V} x5_{pkwvt} -$$

$$\sum_{n}^{N}\sum_{v}^{V} x6_{pknvt} - \sum_{l}^{L}\sum_{v}^{V} x7_{pklvt} - \delta.\left\{\sum_{r}^{R}\sum_{v}^{V} x4_{prkvt} + \sum_{j}^{J}\sum_{v}^{V} RE_{pjt}\,.y5_{jkv}\right\} \forall p, \forall k, \forall t \qquad (5.35)$$

$$\sum_{p}^{P} PS1_p.I1_{pit} + \sum_{c}^{C} CS_c\,.I5_{cit} \leq TSCap1_i \qquad \forall i \in I, \forall t \in T \qquad (5.36)$$

$$\sum_{p}^{P} PS1_p\,.I2_{pdt} + \sum_{p'}^{P'} PS2_{p'}.I3_{p'dt} \leq \sum_{\tau=1}^{t}\sum_{q}^{Q} MICap1_q\,.y9_{qd\tau} \qquad \forall d \in D, \forall t \in T \qquad (5.37)$$

$$\sum_{p}^{P} PS1_p.I4_{pkt} \leq \sum_{\tau=1}^{t}\sum_{q}^{Q} MICap2_q\,.y10_{qk\tau} \qquad \forall k \in K, \forall t \in T \qquad (5.38)$$

$$\sum_{q}^{Q} y9_{qdt} \leq y2_{dt} \qquad \forall d \in D, \forall t \in T \qquad (5.39)$$

$$\sum_{q}^{Q} y10_{qkt} \leq y3_{kt} \qquad \forall k \in K, \forall t \in T \qquad (5.40)$$

$$\sum_{i}^{I}\sum_{v}^{V}\sum_{p}^{P} x1_{pidvt} + \sum_{l}^{L}\sum_{v}^{V}\sum_{p'}^{P'} x8_{p'ldvt} \leq \sum_{\tau=1}^{t}\sum_{q}^{Q} MHCap1_q\,.y9_{qd\tau} \qquad \forall d \in D, \forall t \in T \qquad (5.41)$$

$$\sum_{r}^{R}\sum_{v}^{V}\sum_{p}^{P} x4_{prkvt} + \sum_{j}^{J}\sum_{v}^{V}\sum_{p}^{P} RE_{pjt}\,.y5_{jkv} \leq \sum_{\tau=1}^{t}\sum_{q}^{Q} MHCap2_q\,.y10_{qk\tau} \qquad \forall k \in K, \forall t \in T \qquad (5.42)$$

$$\sum_{d}^{D}\sum_{v}^{V} x2_{pdrvt} = D1_{prt} \qquad \forall p \in P, \forall r \in R, \forall t \in T \qquad (5.43)$$

$$\sum_{d}^{D}\sum_{v}^{V} x3_{p'drvt} = D2_{p'rt} \qquad \forall p' \in P', \forall r \in R, \forall t \in T \qquad (5.44)$$

$$\sum_{d}^{D}\sum_{v}^{V} x2_{pdrvt} \,.\, \alpha_p = \sum_{k}^{K}\sum_{v}^{V} x4_{prkvt} \qquad \forall p \in P, \forall r \in R, \forall t \in T \qquad (5.45)$$

$$\sum_{b}^{B} RTR_{plbt} = \theta_{pl} . \sum_{k}^{K}\sum_{v}^{V} x7_{pklvt} \qquad \forall p \neq 1 \in P \text{ and }, \forall l \in L, \forall t \in T \qquad (5.46)$$

$$\sum_{n}^{N}\sum_{v}^{V} x9_{plnvt} = (1-\theta_{pl}) . \sum_{k}^{K}\sum_{v}^{V} x7_{pklvt} \qquad \forall p \in P, \forall l \in L, \forall t \in T \qquad (5.47)$$

$$\sum_{b}^{B} REC_{pnbt} = \sum_{k}^{K}\sum_{v}^{V} x6_{pknvt} \,.\, B_p + \sum_{l}^{L}\sum_{v}^{V} x9_{plnvt} \,.\, B_p \qquad \forall p \in P, \forall n \in N, \forall t \in T \qquad (5.48)$$

$$\sum_{i}^{I}\sum_{v}^{V} x10_{cnivt} + Qs_{cnt} \leq \sum_{p}^{P}\sum_{b}^{B} REC_{pnbt} \,.\, We_p . a_{cp} \qquad \forall c \in C, \forall n \in N, \forall t \in T \qquad (5.49)$$

$$\sum_{d}^{D}\sum_{v}^{V} x8_{p'ldvt} \leq \sum_{b}^{B} RTR_{plbt} \qquad \forall p \in P, p' \in P', l \in L, \forall t \in T \qquad (5.50)$$

$$\sum_{k}^{K}\sum_{v}^{V} y5_{jkv} = 1 \qquad \forall j \in J \qquad (5.51)$$

$$\sum_{p}^{P}\sum_{i}^{I}\sum_{v}^{V} x1_{pidvt} + \sum_{p'}^{P}\sum_{l}^{L}\sum_{v}^{V} x8_{p'ldvt} \geq MT1_d . y2_{dt} \qquad \forall d \in D, \forall t \in T \qquad (5.52)$$

$$\sum_{p}^{P}\sum_{r}^{R}\sum_{v}^{V} x4_{prkvt} + \sum_{p}^{P}\sum_{j}^{J}\sum_{v}^{V} RE_{pjt} \,.\, y5_{jkv} \geq MT2_k . y3_{kt} \qquad \forall k \in K, \forall t \in T \qquad (5.53)$$

$$\sum_{p'}^{P'}\sum_{d}^{D}\sum_{v}^{V} x8_{p'ldvt} \geq MT3_l . y1_{lt} \qquad \forall l \in L, \forall t \in T \qquad (5.54)$$

$$\sum_{c}^{C}\sum_{i}^{I}\sum_{v}^{V} x10_{cnivt} \geq MT4_n \,.\, y4_{nt} \qquad \forall n \in N, \forall t \in T \qquad (5.55)$$

$$\sum_{p}^{P}\sum_{d}^{D} x1_{pidvt} \,.\, We_p \leq TCap1_{ivt} \qquad \forall i \in I, \forall v \in V, \forall t \in T \qquad (5.56)$$

$$\sum_{p}^{P}\sum_{r}^{R} x2_{pdrvt} \,.\, We_p + \sum_{p'}^{P'}\sum_{r}^{R} x3_{p'drvt} \,.\, We1_{p'} \leq TCap2_{dvt} \qquad \forall d \in D, \forall v \in V, \forall t \in T \qquad (5.57)$$

$$\sum_{p}^{P}\sum_{k}^{K} x4_{prkvt} \,.\, We_p \leq TCap3_{rvt} \qquad \forall r \in R, \forall v \in V, \forall t \in T \qquad (5.58)$$

$$\sum_{p}^{P}\sum_{k}^{K} y5_{jkv} \,.\, RE_{pjt} \,.\, We_p \leq TCap4_{jvt} \qquad \forall j \in J, \forall v \in V, \forall t \in T \qquad (5.59)$$

$$\sum_{p}^{P}\sum_{w}^{W} x5_{pkwvt}.We_p + \sum_{p}^{P}\sum_{n}^{N} x6_{pknvt}.We_p + \sum_{p}^{P}\sum_{l}^{L} x7_{pklvt}.We_p \leq TCap5_{kvt}$$

$\forall k \in K, \forall v \in V, \forall t \in T$ (5.60)

$$\sum_{p'}^{P'}\sum_{d}^{D} x8_{p'ldvt}.We1_{p'} + \sum_{p}^{P}\sum_{n}^{N} x9_{plnvt}.We_p \leq TCap6_{lvt} \quad \forall l \in L, \forall v \in V, \forall t \in T \quad (5.61)$$

$$\sum_{c}^{C}\sum_{i}^{I} x10_{cnivt} \leq TCap7_{nvt} \quad \forall n \in N, \forall v \in V, \forall t \in T \quad (5.62)$$

$y1_{lt} \leq y1_{lt+1}$ $\forall l \in L, \forall t \in T$ (5.63)

$y2_{dt} \leq y2_{dt+1}$ $\forall d \in D, \forall t \in T$ (5.64)

$y3_{kt} \leq y3_{kt+1}$ $\forall k \in K, \forall t \in T$ (5.65)

$y4_{nt} \leq y4_{nt+1}$ $\forall n \in N, \forall t \in T$ (5.66)

$y1_{lt}, y2_{dt}, y3_{kt}, y4_{nt}, y5_{jkv}, y6_{ib}, y7_{lb}, y8_{nb}, y9_{qdt}, y10_{qkt} \in (0,1)$ (5.67)

$Q_{pibt}, RTR_{plbt}, REC_{pnbt}, x1_{pidvt}, x2_{pdrvt}, x3_{p'drvt}, x4_{prkvt}, x5_{pkwvt}, x6_{pknvt}, x7_{pklvt},$

$x8_{p'ldvt}, x9_{plnvt} \geq 0,$ $\quad$ *and integer* (5.68)

*All other variables are continuous.* (5.69)

The objectives of the proposed model shown in (5.1) and (5.14) are to maximize the total profit of the overall system and to minimize the total environmental impact along the CLSC network, respectively. Constraints (5.25)-(5.27) ensure that the production, remanufacturing and recycling quantities with the selected technology must not exceed the capacities of these facilities. Constraints (5.28)-(5.30) represent the selection of only one environmental protection technology by the opened facilities for each time period. According to the constraint set (5.31) to (5.35), one can calculate the inventory levels of each type of brand new tire and material at each new tire plant, inventory levels of each type of brand new and retreaded tire at each distribution center and finally inventory levels of each type of scrap tire at each centralized return point in each time period. Constraints (5.36)-(5.38) are storage capacity constraints for new tire plants, distribution centers and centralized return points, respectively. Inventory levels at each opened distribution center and centralized return point cannot get over the capacity of integrated module. Constraints (5.39) and (5.40) make sure that only one capacity module can be integrated to the opened distribution center or centralized return point in each time period. Inbound handling capacities of the distribution centers and centralized return points are restricted by the constraints (5.41) and (5.42). Constraints (5.43) and

(5.44) ensures that demands for each brand new and retreaded tire type of each tire dealer in each time period must fully be satisfied. Constraint (5.45) is the flow constraint balancing the quantities of returned tires. Constraints (5.46) and (5.47) are conservation of flow constraints for retreading companies. One can calculate the amounts of each type of recyclable tire by using constraint (5.48). According to the constraint (5.49), sum of the shipped recycled material amounts to the new tire plants and sold recycled material amounts to third party applications cannot exceed the total amounts of material obtained from the used tires in recycling phase. Similarly in constraint (5.50), quantity of transferred retreaded tires from the retreading companies to distribution centers cannot pass the level of remanufacturing. Constraint (5.51) ensures that an initial collection center can be assigned to single centralized return point with the usage of only one vehicle type. Constraints set (5.52) to (5.55) represent the minimum throughput constraints which allow the opening of facilities in the case of exceeding pre-determined levels. Constraints (5.56)-(5.62) reflect the vehicle capacity limits departing from new tire plants, distribution centers, tire dealers, initial collection centers, centralized return points, retreading companies and tire recycling facilities, respectively during each time period. Constraints (5.63)-(5.66) guarantee that when a facility is installed, it remains open until the end of planning period. Constraint (5.67) assures the binary integrality of decision variables. Constraint (5.68) and (5.69) preserve the non-negativity of decision variables. It is noted that variables related to production, remanufacturing, recycling and transportation take integer values.

## 5.5 Computational Case Study

### *5.5.1 Data Description and Results of Deterministic Models*

In order to see the usefulness, validity and practicality of the proposed model, a case study is derived which depends on inspiration from tire industry case in Aegean region of Turkey. The CLSC network involves two new tire plants, four potential sites for distribution centers, twenty tire dealers, five initial collection centers, four potential sites for centralized return points, three potential locations for tire retreading companies, two potential sites for tire recycling facilities and two cement kilns as energy recovery centers. There are also three types of brand new and retreaded tires namely passenger car, truck and bus tires, three types of materials/components namely steel, rubber and fiber. The planning period is four quarter and composed of three months. Three types of vehicles can be used for the transportation processes which have different capacities, costs and environmental impact. Finally, three types of module capacity and three types of environmental protection technology are available for capacity expansion and environmental improvements, respectively. Configuration of the computational case study is shown in Figure 5.6.

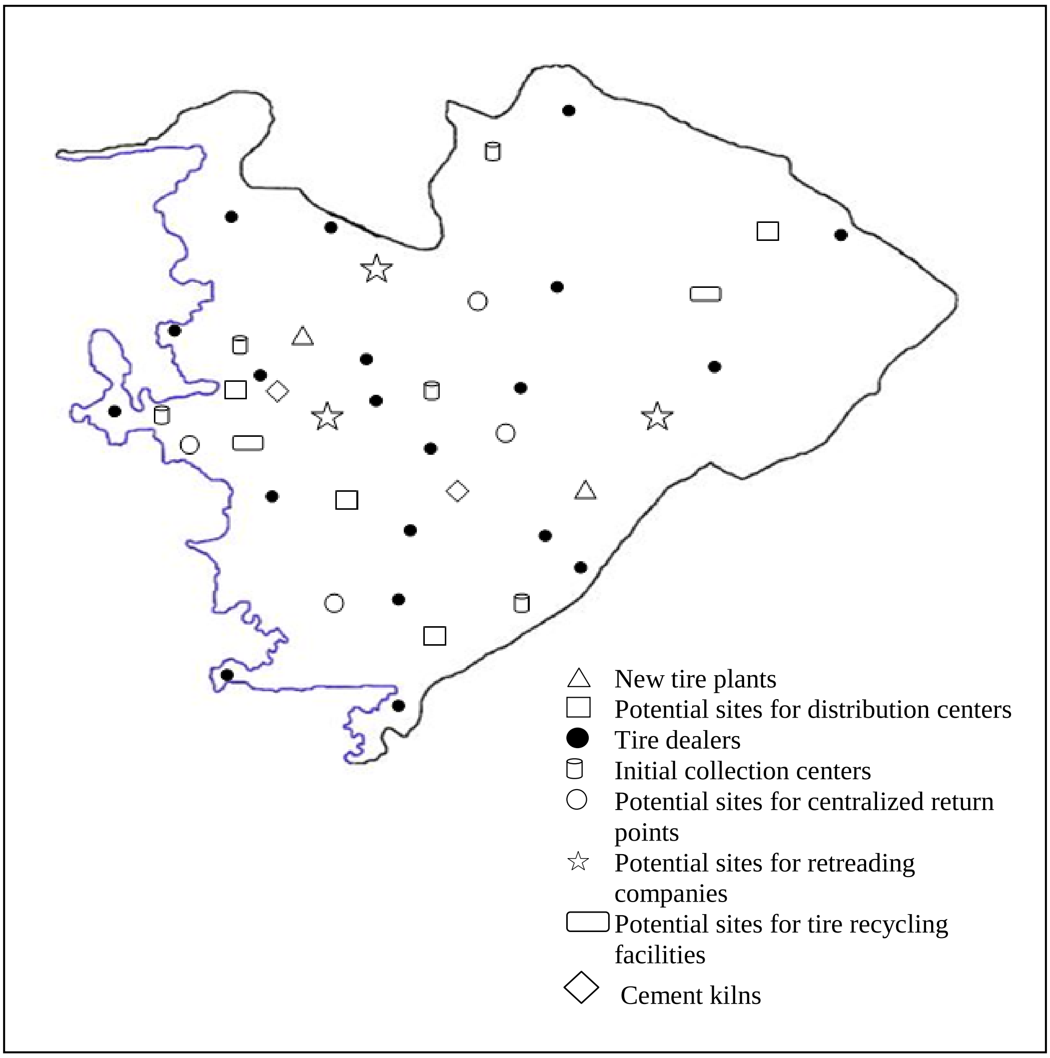



Figure 5.6 Nodes in the computational case study

The following data are used for testing the proposed model:

- The discount selling prices of brand new tires are \$100, \$400 and \$350 for passenger car, truck and bus tires, respectively. Selling prices of the tires without any returns are \$150, \$480 and \$420.
- Selling prices of the retreaded tires for meeting the secondary market's requirements are \$50, \$200 and \$175.
- Selling prices of scrap tires to the cement kilns etc. for energy recovery option are \$5, \$8 and \$7.
- Selling prices of one kg of recycled materials for third party applications are \$3, \$1.4 and \$1.
- Unit transportation costs of the brand new tires using truck 16t, truck 28t and truck 40t are \$0.012, \$0.017, \$0.022 for passenger car tires, \$0.022, \$0.02, \$0.025 for truck tires and \$0.02, \$0.022, \$0.024 for bus tires. Unit transportation costs of the retreaded tires using truck 16t, truck 28t and truck 40t are \$0.01, \$0.015, \$0.02 for passenger car tires, \$0.02, \$0.018, \$0.023 for truck tires and \$0.018, \$0.02, \$0.022 for bus tires. Similarly, transportation costs for per kg of recycled materials using truck 16t, truck 28t and truck 40t are \$0.0006, \$0.0007, \$0.008 for steel wires, \$0.0005, \$0.0006, \$0.0007 for rubber powder and \$0.0004, \$0.0005, \$0.0006 for fibers.
- Return fraction of used tires from the tire dealers directly are %60, %80 and %70 for all types of tires.
- Minimum disposal rates for the scrap tires are %15, %8 and%8.
- Quality specification rates for the recycling process are %80, %90 and %80 for passenger car, truck and bus tires, respectively.
- Weights of the tires are taken as 7 kg, 30 kg and 25 kg.
- Some of the other monetary data which is used in the case study are given in Tables 5.2 and 5.3.

In Table 5.2, three costs included in each cell which represent the related cost values of production, remanufacturing and recycling by use of different environmental protection technology from 1 to 3.

Table 5.2 Product information

| Tire type | Production cost ($) | | Retreading cost ($) | | | Recycling cost ($) | |
|---|---|---|---|---|---|---|---|
| | Plant1 | Plant2 | Comp.1 | Comp.2 | Comp.3 | Fac.1 | Fac.2 |
| Car | 50, 40, 30 | 45, 35, 30 | 8, 6, 4 | 7, 5, 3 | 8, 4, 3 | 2, 1.5, 1 | 1.8,1.3,0.8 |
| Truck | 180,160,140 | 200,180,150 | 30, 25, 20 | 28, 26, 20 | 30, 24, 18 | 5, 4, 3.5 | 4, 3.5, 3 |
| Bus | 150,130,100 | 150,130,110 | 25, 22, 19 | 26, 23, 20 | 25, 21, 20 | 3, 2.5, 2 | 3.2, 2.4, 2 |

For instance, unit production cost in plant 1 for passenger car tire is $50 by using environmental protection technology 1, $40 by using environmental protection technology 2 and $30 by using environmental protection technology 3. As it can be seen from Table 5.3, set-up costs for the facilities at the potential locations (L) will be increased based on the time.

Table 5.3 Fixed opening costs for the facilities (in millions $)

| Period | Retreading companies | | | Distribution centers | | | | Centralized return points | | | | Recycling facilities | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | L1 | L2 | L3 | L1 | L2 | L3 | L4 | L1 | L2 | L3 | L4 | L1 | L2 |
| First quarter | 5.5 | 5 | 4.5 | 1.5 | 1.2 | 1.5 | 1.3 | 1 | 0.9 | 1.2 | 1.8 | 6.0 | 6.5 |
| Second quarter | 5.6 | 5.1 | 5 | 1.7 | 1.5 | 1.6 | 1.4 | 1.1 | 1 | 1.3 | 1.9 | 6.3 | 6.8 |
| Third quarter | 5.7 | 5.2 | 5.2 | 1.8 | 1.8 | 1.7 | 1.5 | 1.2 | 1.1 | 1.4 | 2 | 6.5 | 6.9 |
| Fourth quarter | 5.8 | 5.3 | 5.3 | 2 | 1.9 | 1.8 | 1.6 | 1.3 | 1.2 | 1.5 | 2.1 | 6.7 | 7.0 |

Data related to the environmental parameters are generated based on the results of related papers (Corti and Lombardi, 2004; Ferrao, Ribeiro, and Silva, 2008) and expressed in eco-indicator 99 points as it can be seen from the following figures (from Figure 5.7 to Figure 5.16).

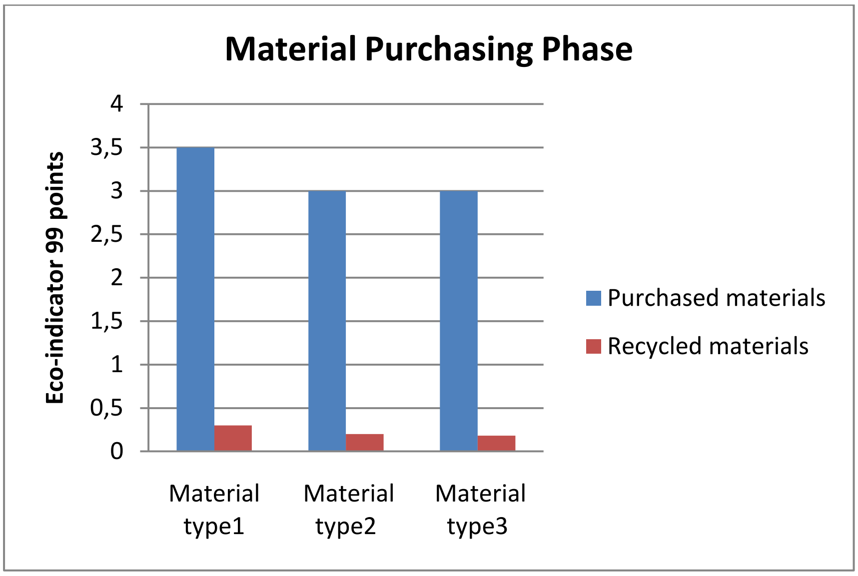



Figure 5.7 Impact of material purchasing phase on the environment

In the material purchasing phase, it can be obviously seen that usage of recycled materials in the production has less environmental effect than purchasing them from the external suppliers.

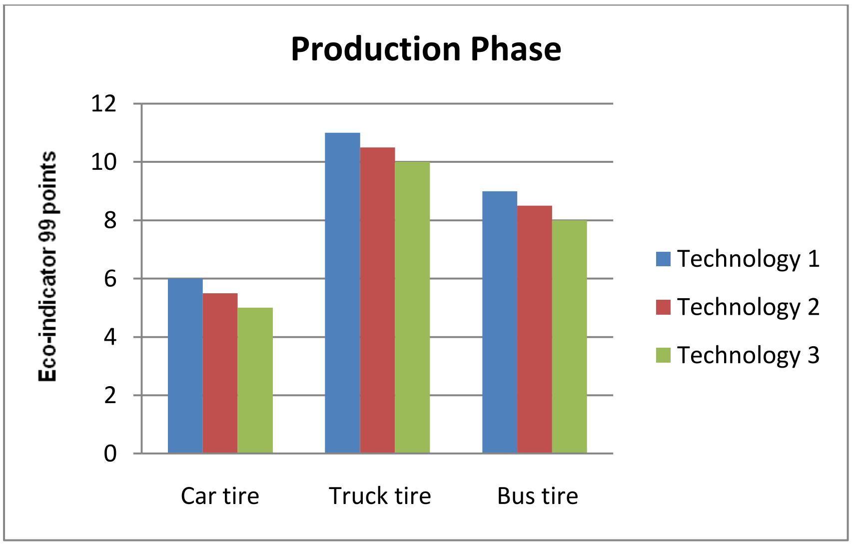



Figure 5.8 Impact of production phase on the environment

In the production phase, although the investment cost of the environmental protection technology-1 is cheaper than the others, it has more impact on the environment.

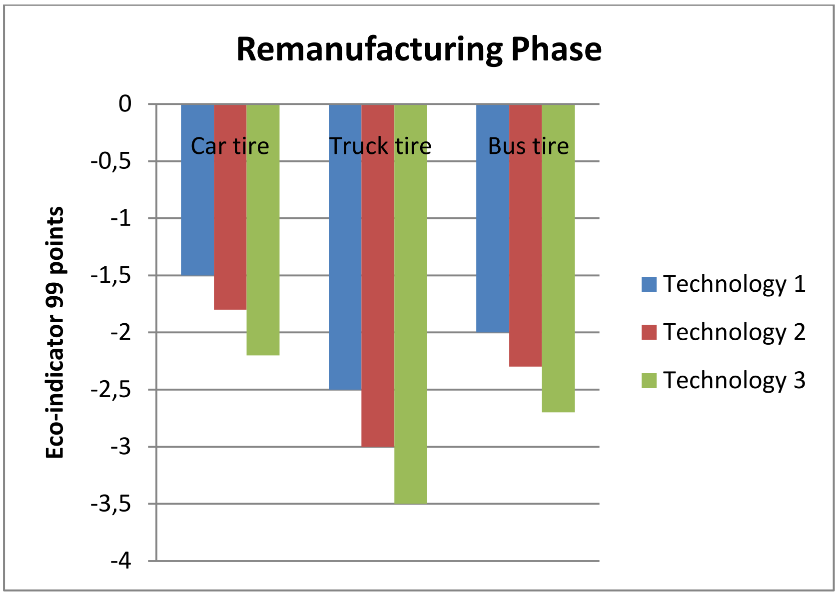



Figure 5.9 Impact of retreading phase on the environment

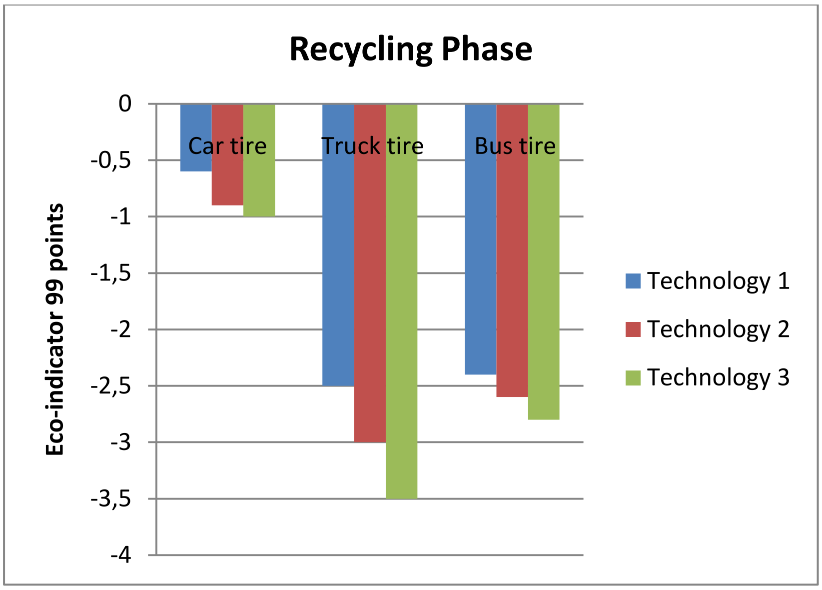



Figure 5.10 Impact of recycling phase on the environment

As it can be seen from Figures 5.9 and 5.10, environmental gains are yielded in the remanufacturing and recycling phases. The most advanced environmental protection technology (technology-3) provides the most environmental production, remanufacturing and recycling operations but causes most costly way.

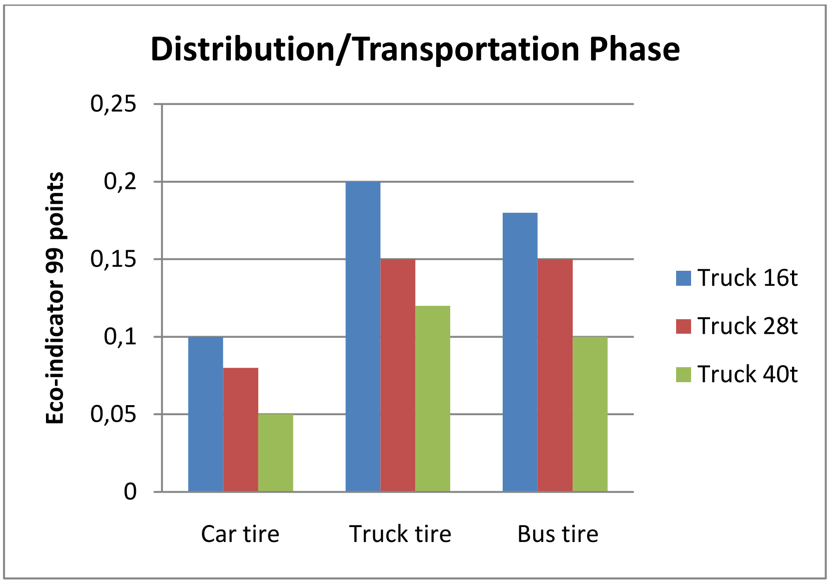



Figure 5.11 Impact of distribution phase on the environment

In the transportation phase, in spite of rental cost for truck 40t is more expensive, this type of vehicle is more environmental friendly way of distribution.

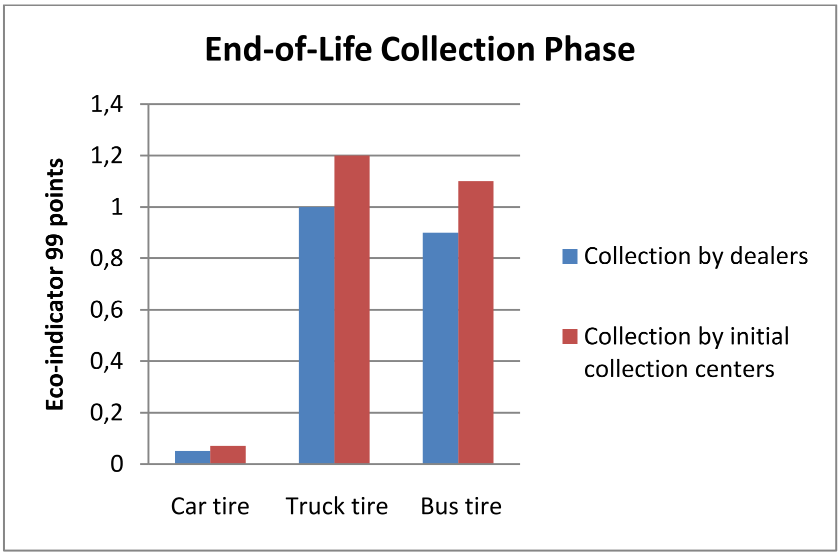



Figure 5.12 Impact of collection phase on the environment

In the end-of-life collection phase, accumulating the scrap tires from the end users by the initial collection centers is more costly and also less environmental conscious way of the collection.

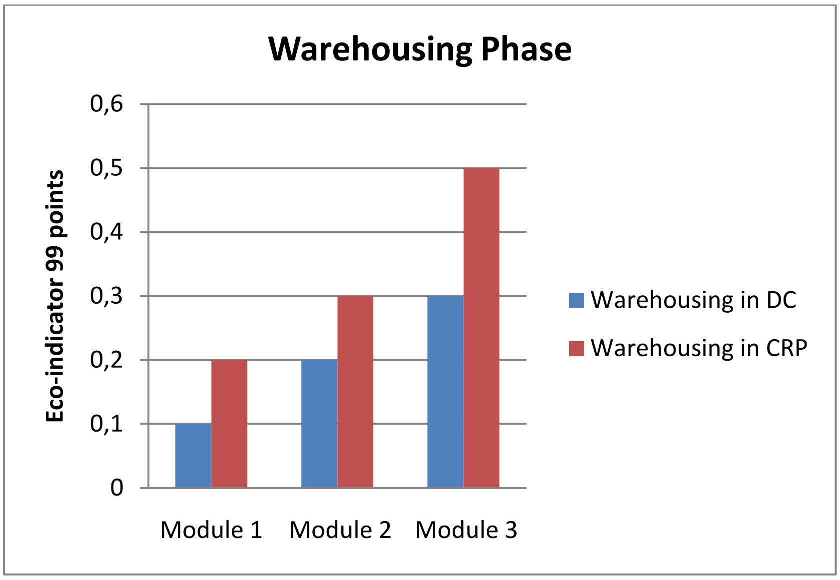



Figure 5.13 Impact of warehousing phase on the environment

In the warehousing phase, when the capacity of the used module is increased, environmental damage also increases. In addition, intensity of the environmental damage is more solid in centralized return points since the storage of scrap tires.

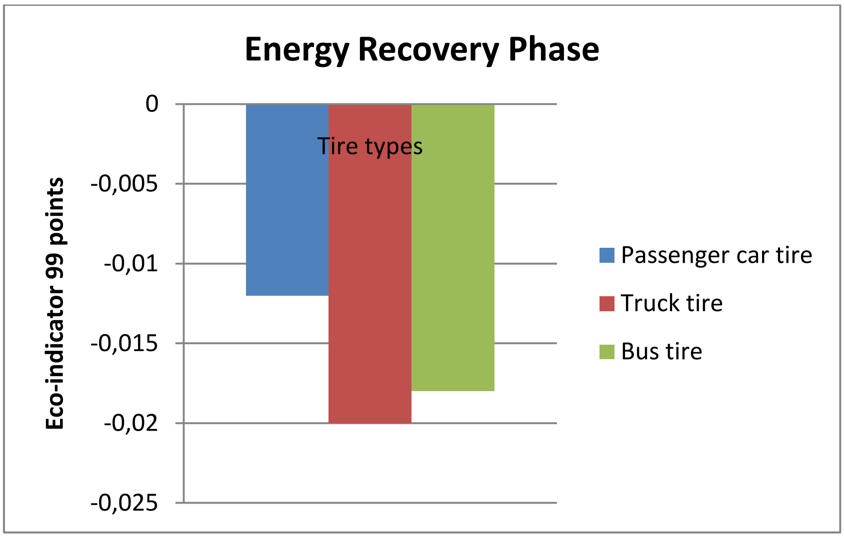



Figure 5.14 Impact of incineration in cement kilns on the environment

Energy recovery phase has also positive environmental impact as the remanufacturing and recycling phases.

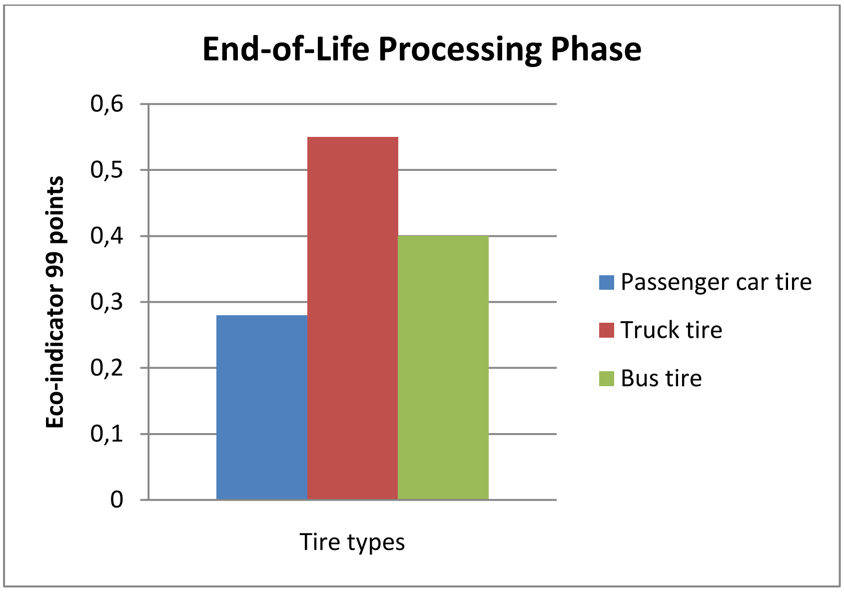



Figure 5.15 Impact of end-of-life processing phase on the environment

In the disposal phase, land filling causes larger environmental damage than the incineration. However, environmental impacts of the disposition process also become larger in the case of increased tire size.

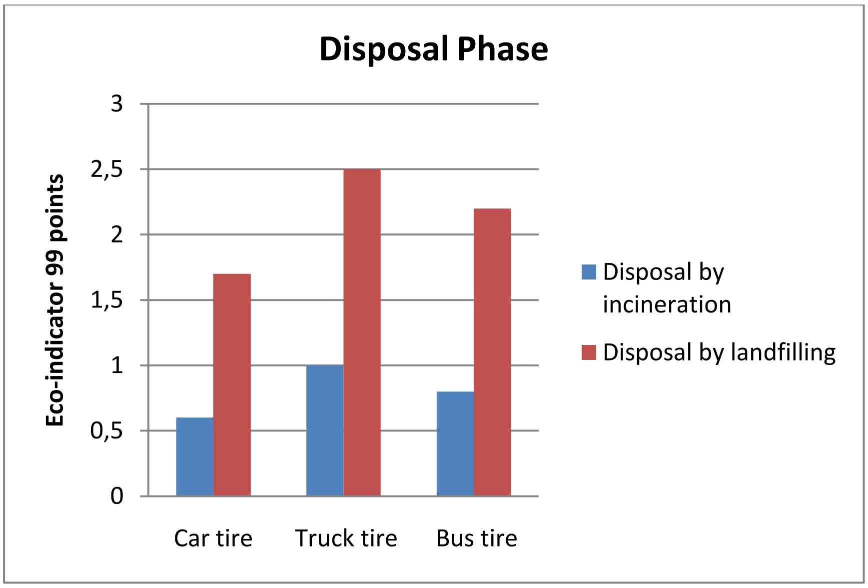



Figure 5.16 Impact disposal phase on the environment

Remaining data ranges used in the case study are given in Table 5.4.

Table 5.4 Parameter intervals used in the case study

| Parameters | Range of values |
|---|---|
| Rental and operating cost of retreading companies | $35000-$50000 |
| Rental and operating cost of distribution centers | $10000-$20000 |
| Rental and operating cost of centralized return points | $6000-$13000 |
| Rental and operating cost of tire recycling facilities | $60000-$70000 |
| Investment costs of environmental protection technologies in new tire plants | $100000-$200000 |
| Investment costs of environmental protection technologies in retreading companies | $80000-$120000 |
| Investment costs of environmental protection technologies in recycling facilities | $90000-$150000 |
| Installing costs of capacity modules in distribution centers | $50000-$100000 |
| Installing costs of capacity modules in centralized return points | $55000-$110000 |
| Material purchasing costs from the external suppliers | $0.8-$2.5 |
| Collection costs by the initial collection centers | $0.008-$0.01 |
| Inventory holding costs of brand new tires in tire plants | $0.8-$1.2 |
| Inventory holding costs of brand new tires in distribution centers | $0.8-$1.2 |
| Inventory holding costs of retreaded tires in distribution centers | $0.6-$1 |
| Inventory holding costs of scrap tires in centralized return points | $0.5-$0.9 |
| Inventory holding costs of materials in tire plants | $0.001-$0.005 |
| Incineration costs at the disposal sites | $0.5-$0.8 |
| Landfill costs at the disposal sites | $0.2-$0.4 |
| Contributions of materials (%) in the tires | %3-%45 |
| Unit storage capacity consumption factor for brand and retreaded new tires | 0.05-0.2 |
| Unit storage capacity consumption factor for materials | 0.0008-0.00013 |
| Recovery fraction for retreading process (except passenger car tires) | %70-%90 |
| Distances between all stages | 16-345 km. |
| Demand for brand new passenger car tires | Uniform (1000,2000) |
| Demand for brand new truck and bus tires | Uniform (600,1200) |
| Demand for retreaded truck and bus tires | Uniform (300,900) |
| Returned volumes through the initial collection centers | Uniform (200,500) |
| Total production capacities of new tire plants | 40000-80000 units |
| Total remanufacturing capacities of retreading companies | 24000-72000 units |
| Total recycling capacities of recycling facilities | 40000-76000 units |
| Total storage capacities of new tire plants | 1000-1500 units |
| Module storage capacities for distribution centers | 500-1500 units |
| Module storage capacities for centralized return points | 1000-3000 units |
| Module inbound handling capacities for distribution centers | 20000-50000 units |
| Module inbound handling capacities for centralized return points | 30000-70000 units |
| Minimum throughputs for opening of distribution centers | 2000 units |
| Minimum throughputs for opening of centralized return points | 3000 units |
| Minimum throughputs for opening of retreading companies | 1000 units |
| Minimum throughputs for opening of tire recycling facilities | 10000 units |
| Transportation weight capacity of truck 16t | 16000 kg. |
| Transportation weight capacity of truck 28t | 28000 kg. |
| Transportation weight capacity of truck 40t | 40000 tones |

When we run the model with these data through a mixed integer programming solver ILOG OPL Studio version 6.3 including CPLEX 12.1.0 product on an Intel Core i7 2 GHz IBM PC for the first objective function and the second one separately as a single objective integer programming model; we can obtain the following optimization results and independent objective function values as shown in the Table 5.5. Furthermore, Figures 5.17 and 5.18 display the corresponding optimal network structures for each objective function at the end of the last quarter (Quarter 4). According to Figure 5.17, all of the forward and reverse flows are existed between the nodes that are as possible as closest to each other due to the transportation costs. In addition, recycled materials are only used in new tire plant-1. Plant-2 purchased required materials from the external suppliers since the long distances and low purchasing costs commitments for this plant.

Table 5.5 Optimization results obtained from the deterministic model solution considering objective functions separately

| | **Total profit objective-1** | **Overall eco-indicator 99 score objective-2** |
|---|---|---|
| Total number of variables | 11474 | 11618 |
| Total number of integer variables | 9612 | 9612 |
| Total number of binary variables | 229 | 229 |
| Total number of constraints | 1956 | 1900 |
| Total number of iterations | 258373 | 6782 |
| Total revenue of the CLSC | $113490000 | $93780000 |
| Total cost of the CLSC | $65442000 | $76714000 |
| Total Eco-indicator score | 43137000 mPt | 15208362.27 mPt (total |
| LP relaxation value | $48044171.09 (total profit) | eco-indicator 99 score) |
| Solving time (second) | 110.24 | 72.94 |
| Optimality gap (%) | - | - |
| Number of opened retreading companies | 1 | 2 |
| Number of opened tire recycling facilities | 2 | 2 |
| Number of opened distribution centers | 2 | 4 |
| Number of opened centralized return points | 4 | 4 |

Apart from the first optimal configuration, additional two distribution centers and one retreading company should also be opened in Figure 5.18. The second configuration presents more environmental friendly but less profitable CLSC network. It can also obviously be seen that there is no scrap tires sales to the cement kilns. All of the scrap tires are either remanufactured or recycled since these options yield more environmental profit than the energy recovery option.

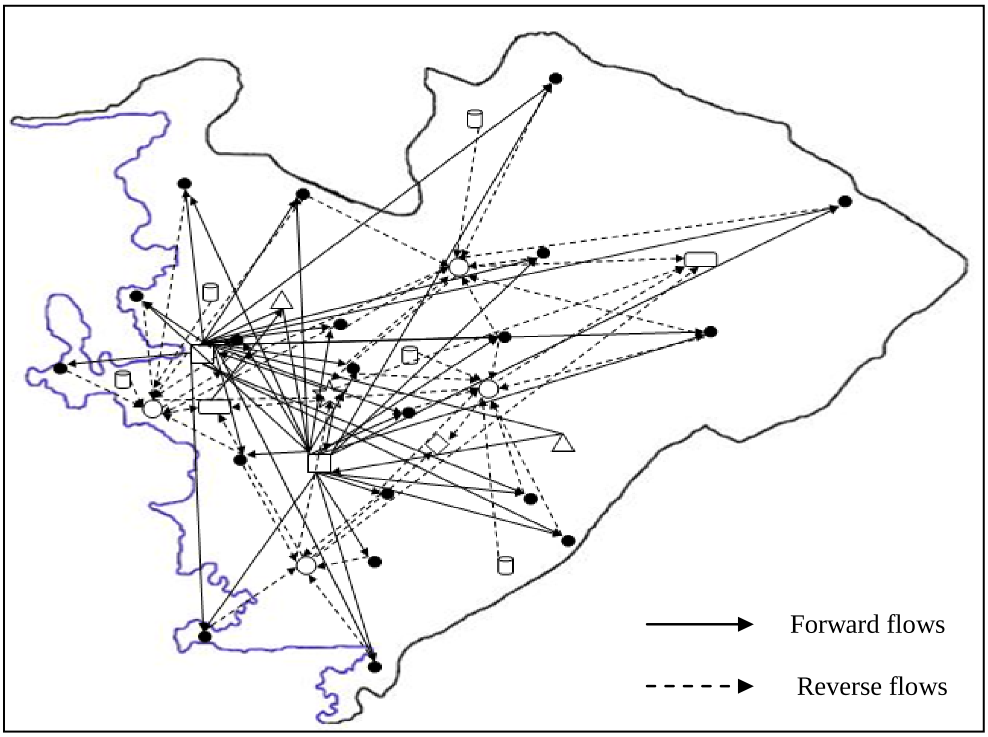



Figure 5.17 Optimal CLSC network at the end of last quarter considering only first goal (profit maximization)

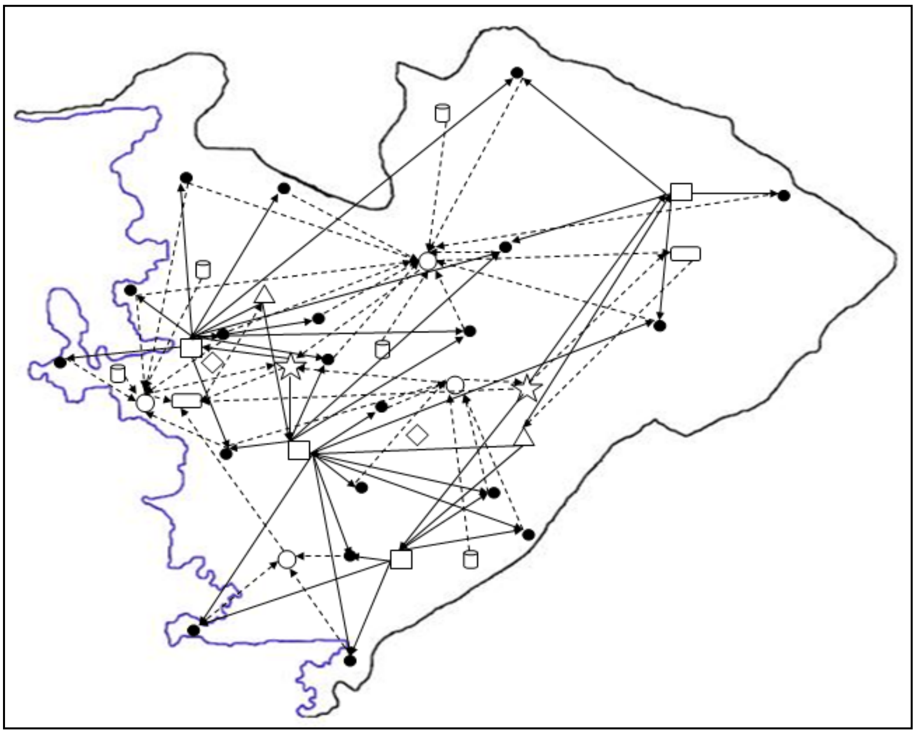


Figure 5.18 Optimal CLSC network at the end of last quarter with only second goal (eco-indicator 99 score minimization)

### *5.5.2 Optimization Results via Interactive Fuzzy Goal Programming Approach*

In this section, interactive fuzzy goal programming approach is employed in order to solve the multiple objective CLSC network design problem. This approach first introduced by Abd El-Wahed and Lee (2006) and applied to multi-objective transportation problems in order to determine the preferred compromise solution. In this method, three commonly used approaches namely interactive programming, goal programming and fuzzy programming are integrated in order to generate more efficient method which reflects the advantages of all these approaches.

From the perspective of DM, the most important advantage of this method is controlling the search direction during the solution phase by updating the both upper bounds and aspiration level of each goal for providing other optimal solutions. The solution which is obtained from the last iteration and accepted by the DM represents the preferred compromise solution and perceived as a more realistic one.

In supply chain, RL and CLSC network design concept, this method is applied and modified by Mirakhorli (2010), Zarandi, Sisakht, and Davari (2011). The application procedure of this approach is shown in Figure 5.19.

Mathematical formulation of the multi-objective, multi-echelon, multi-product and multi-period CLSC network design problem in tire industry is given in section 5.4.5. A payoff matrix can be derived as shown in Table 5.6 by using the efficient solutions that are given in Table 5.5.

Table 5.6 Payoff matrix

| Goals | Total CLSC profit | Total Eco-indicator score |
|---|---|---|
| **Total CLSC profit** | $48044171.09 | 43137000 mPt |
| **Total Eco-indicator score** | $17066000 | 15208362.27mPt |

Membership function of each fuzzy goal and corresponding analytical definitions are depicted based on Zimmermann (1976) in the following Figures 5.20 and 5.21 for the first iteration by using the values provided in Table 5.6.

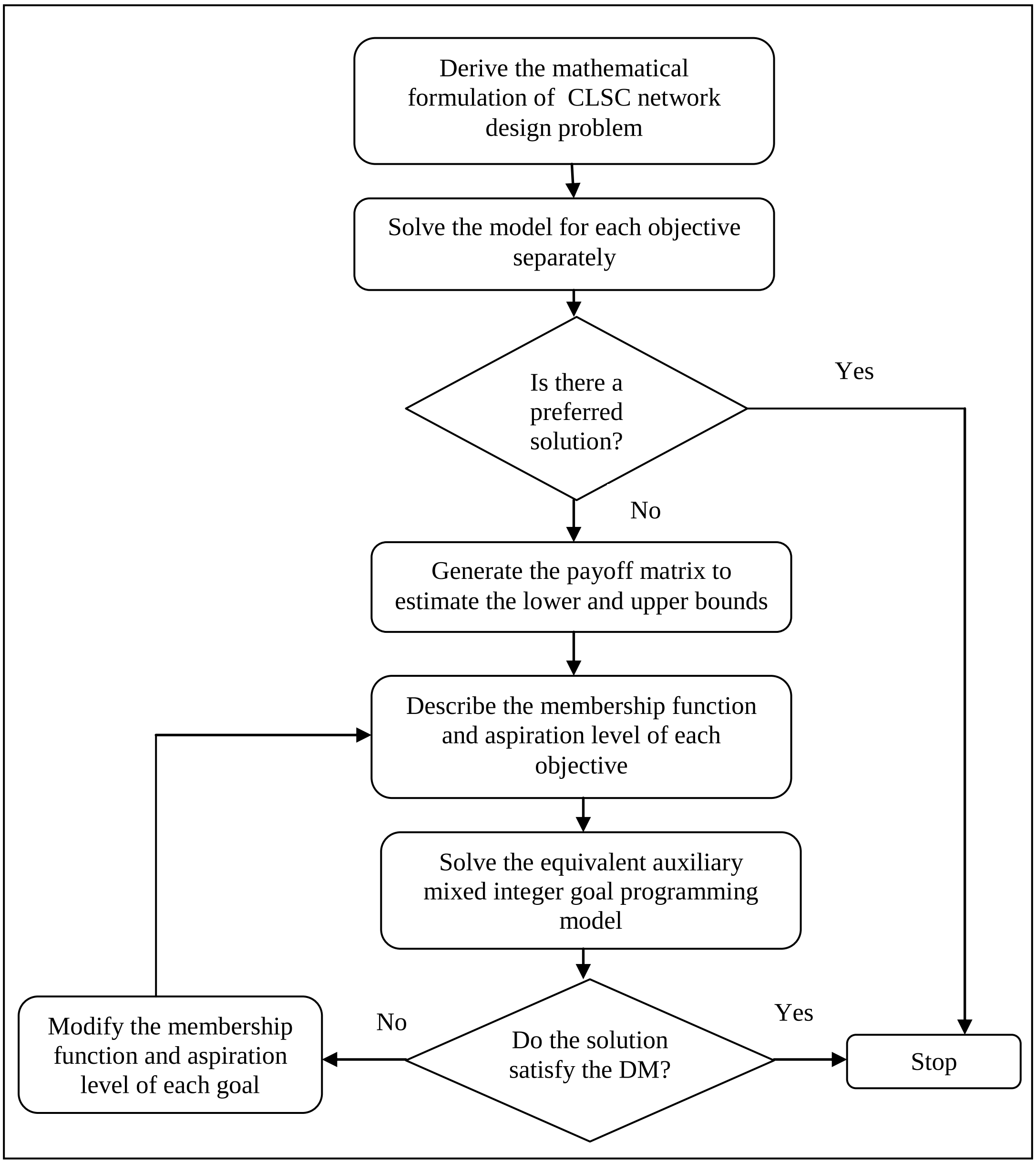



Figure 5.19 Flowchart of the generic IFGP approach

After the definition of the membership functions and aspiration levels, the problem can be transformed into an equivalent crisp auxiliary single objective mixed integer linear programming model as stated in Table 5.7.

$$\mu_1 = \begin{cases} 1, & \text{if } Z_1 \geq 48044171.09 \\ \dfrac{Z_1 - 17066000}{48044171.09 - 17066000}, & \text{if } 17066000 \leq Z_1 \leq 48044171.09 \\ 0, & \text{if } Z_1 \leq 17044171.09 \end{cases}$$

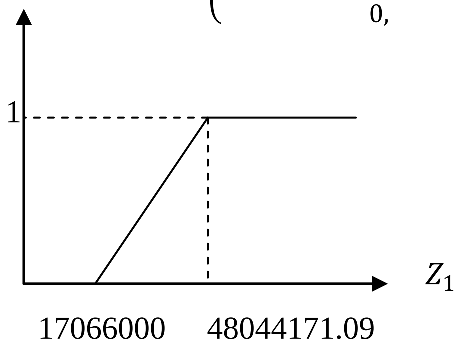



Figure 5.20 Membership function of fuzzy maximum $Z_1$ (Maximize total CLSC profit)

$$\mu_{Z_2} = \begin{cases} 1, & \text{if } Z_2 \leq 15208362.27 \\ \dfrac{43137000 - Z_2}{43137000 - 15208362.27}, & \text{if } 15208362.27 \leq Z_2 \leq 43137000 \\ 0, & \text{if } Z_2 \geq 43137000 \end{cases}$$

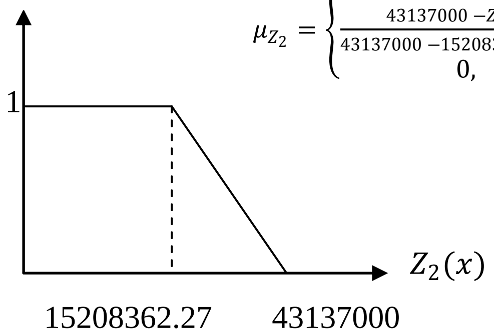



Figure 5.21 Membership function of fuzzy minimum $Z_2$ (Minimize total eco-indicator 99 score)

$$\mu_1 = \begin{cases} 1, & \text{if } Z_1 \geq 48044171.09 \\ \dfrac{Z_1 - 40224000}{48044171.09 - 40224000}, & \text{if } 40224000 \leq Z_1 \leq 48044171.09 \\ 0, & \text{if } Z_1 \leq 40224000 \end{cases}$$

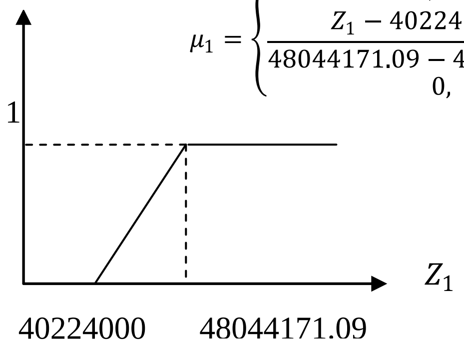



Figure 5.22 Modified membership function of fuzzy maximum $Z_1$ (in iteration 2)

$$\mu_{Z_2} = \begin{cases} 1, & if\ Z_2 \leq 15208362.27 \\ \frac{22259000 - Z_2}{22259000 - 15208362.27}, & if\ 15208362.27 \leq Z_2 \leq 22259000 \\ 0, & if\ Z_2 \geq 22259000 \end{cases}$$

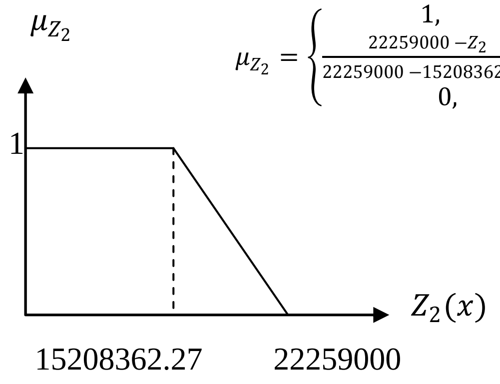



Figure 5.23 Modified membership function of fuzzy minimum $Z_2$ (in iteration 2)

It is assumed that the results of this first iteration have not satisfied the DM yet. Therefore, previous goals' bounds should replace by the newly obtained optimal results. As a result, membership functions can be modified in iteration 2 as seen in Figures 5.22 and 5.23. In other words, membership functions are re-constructed as in iteration 2. According to Figures 5.22 and 5.23, new aspiration levels of the bi-objective functions are 40224000 and 22259000, respectively.

Table 5.7 Corresponding equivalent auxiliary model in iteration 1

| |
|---|
| $Max \quad \beta$ |
| $Subject\ to;$ |
| $Total\ Profit - 30978171.09.\beta \geq 17066000$ |
| $Total\ Eco - indicator\ score + 27928637.7\ .\beta \leq 43137000$ |
| $Total\ Profit - d_1^+ + d_1^- = 17066000$ |
| $Total\ Eco - indicator\ score - d_2^+ + d_2^- = 43137000$ |
| $Constraint\ set\ from\ Eq.(25) to\ Eq.(69)$ |
| $0 \leq \beta \leq 1\ and\ d_1^+, d_1^-, d_2^+, d_2^- \geq 0$ |

Based on the bound modifications, the mathematical model that is given in Table 5.7 is updated and resolved to generate the latter efficient solution in iteration 2. Optimization results provided by solving these auxiliary models iteratively are given in Table 5.8.

Table 5.8 Fuzzy optimization results obtained by all iterations

| Iteration | Auxiliary variable β | Total CLSC profit | Total Eco-indicator 99 score | Solving time (Sec.) |
|---|---|---|---|---|
| 1 | 0.747543 | $40224000 | 22259000 mPt | 521.72 |
| 2 | 0.371706 | $43131000 | 19638000 mPt | 1213.46 |
| 3 | 0.028917 | $43273000 | 19510000 mPt | 452.47 |
| 4 | 0.000441 | $43276000 | 19508000 mPt | 8420.39 |

It is assumed that the DM is satisfied at the end of iteration 4 with the total revenue $101880000 and accepts the relevant solution as the preferred compromise solution. Thus, the procedure configured in Figure 5.19 is terminated. The obtained compromise solution can be elaborated through the following Figures 5.24, 5.25 and 5.26; Tables 5.9, 5.10 and 5.11.

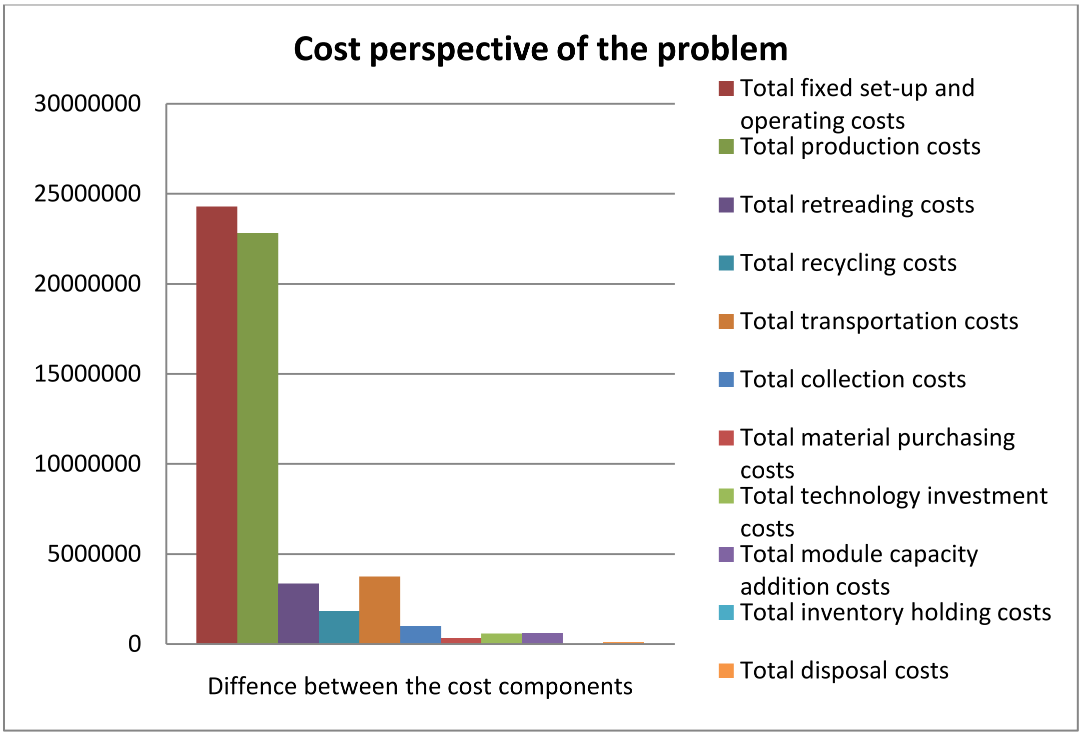



Figure 5.24 Results related to different cost items

According to the Figure 5.24, total fixed opening and operating costs of facilities, production costs, transportation costs as well as retreading costs constitute the large portion of the total CLSC costs.

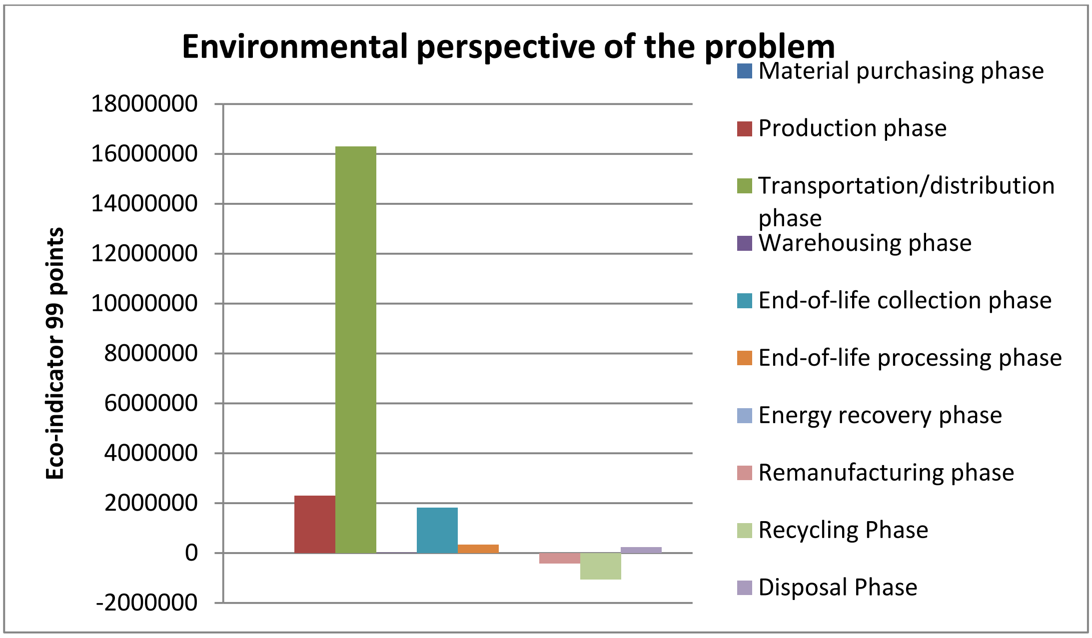



Figure 5.25 Environmental impacts of different life cycle phases in a tire CLSC

Figure 5.25 points out that transportation, production and collection phases have an undeniable impact on the environment. However, recycling and remanufacturing yield positive environmental impact. Since none of the scrap tires are sold to the cement kilns, paper mills and thermoelectric plants, environmental impact of this phase equals to zero. In addition, environmental impact of material purchasing phase also equals to zero because of a balance provided between the quantity of purchase materials and recycled materials.

With this compromise solution, one of the retreading companies, two of the distribution centers, three of the centralized return points and two of the tire recycling facilities will be opened as it can be seen from Figure 5.26.

Selected environmental protection technology levels during the production, remanufacturing and recycling are given in Table 5.9. Furthermore, related quantities of these facilities with the installed technologies are given in Table 5.10. In terms of capacity expansion, all of the opened distribution centers and centralized return points tend to be operated with module type-1 since there are no capacity addition requirements throughout the planning horizon.

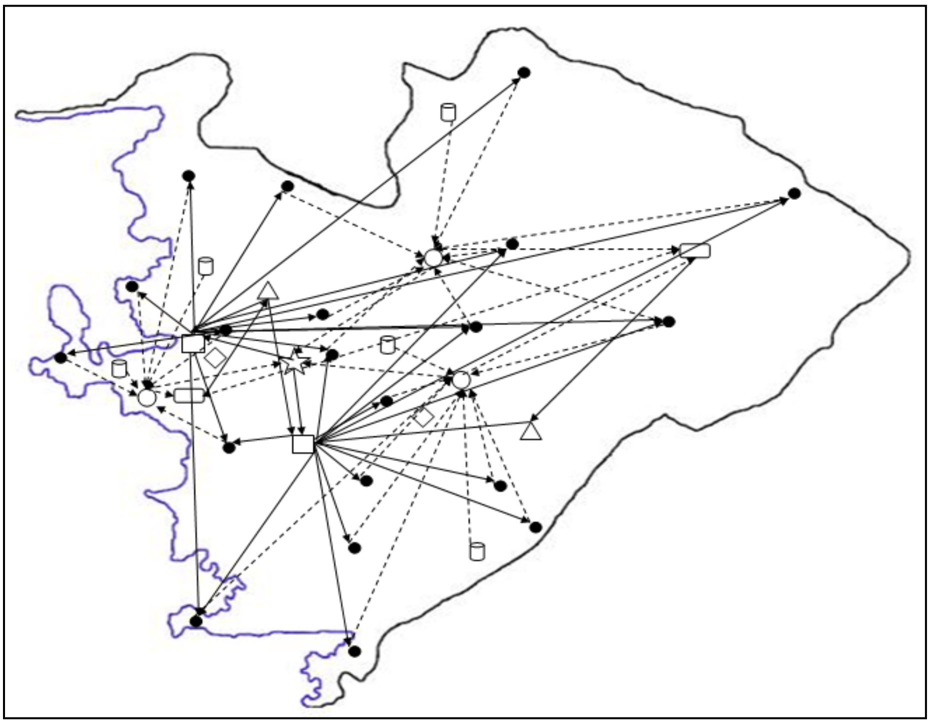


Figure 5.26 Optimal CLSC network at the end of last quarter with consideration of all fuzzy goals simultaneously

Sales quantities of recycled materials from the tire recycling facilities and purchasing quantities of raw materials to the new tire plants are also given in Table 5.11. It is a fact that using the recycled materials in the new tire production is more advantages than purchasing them from the external suppliers. Shipped recycled materials amounts to the new tire plants are also given in Table 5.12.

Table 5.9 Environmental protection technology investment decisions

| | **Production** | | **Remanufacturing** | **Recycling** | |
|---|---|---|---|---|---|
| | Plant-1 | Plant-2 | Retreading company | Facility-1 | Facility-2 |
| Technology-1 | x | x | | | |
| Technology-2 | | | | | x |
| Technology-3 | | | x | x | |

Table 5.10 Production, remanufacturing and recycling quantities

| **Period** | **Production** | | | | | | **Remanufacturing** | | | **Recycling** | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Plant-1 | | | Plant-2 | | | Retreading company | | | Facility-1 | | | Facility-2 | | |
| | Car | Truck | Bus | Car | Truck | Bus | Car | Truck | Bus | Car | Truck | Bus | Car | Truck | Bus |
| Q1 | 12754 | 12640 | 14606 | 16946 | 5910 | 7634 | - | 11900 | 11900 | 53946 | 13719 | 4335 | - | 50074 | - |
| Q2 | 11871 | 12630 | 15499 | 16300 | 6290 | 6162 | - | 12570 | 12570 | 46619 | 20777 | 4604 | 10365 | 47613 | - |
| Q3 | 11090 | 12730 | 16180 | 18039 | 5400 | 7179 | - | 12960 | 12960 | 46391 | 20888 | 4721 | 12361 | 45267 | - |
| Q4 | 10500 | 11220 | 18280 | 15300 | 5090 | 3260 | - | 13240 | 13240 | 46289 | 20888 | 4823 | 13373 | 46075 | - |

Table 5.11 Sales and purchasing quantities of materials (kg.)

| **Period** | **Material sales** | | | | | | **Material purchasing** | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Recycling facility-1 | | | Recycling facility-2 | | | Tire plant-1 | | | Tire plant-2 | | |
| | Steel | Rubber | Fiber | Steel | Rubber | Fiber | Steel | Rubber | Fiber | Steel | Rubber | Fiber |
| Q1 | 2538.6 | 15974 | - | 299540 | 605270 | 55054 | - | - | 2.18 | - | 76139 | - |
| Q2 | 48988 | 96931 | 8622.6 | 300300 | 743230 | 54577 | - | - | - | - | 209310 | - |
| Q3 | 46330 | 92299 | 8191.2 | 282070 | 501350 | 51430 | - | - | - | - | - | - |
| Q4 | 47210 | 93838 | 8560.7 | 321710 | 573720 | 57889 | - | - | - | - | - | - |

Table 5.12Transportation quantities of recycled materials (kg.) from tire recycling facilities to new tire plants

| | | New tire plant-1 | | | New tire plant-2 | | |
|---|---|---|---|---|---|---|---|
| | Period | Steel | Rubber | Fiber | Steel | Rubber | Fiber |
| **Recycling facility-1** | Q1 | 215320 | 389630 | 36242 | - | - | - |
| | Q2 | 219580 | 397050 | 36937 | - | - | - |
| | Q3 | 223580 | 404030 | 36604 | - | - | - |
| | Q4 | 223200 | 403350 | 37315 | - | - | - |
| **Recycling facility-2** | Q1 | - | - | - | 121080 | 145840 | 20058 |
| | Q2 | - | - | - | 114170 | - | 19020 |
| | Q3 | - | - | - | 115480 | 212270 | 19067 |
| | Q4 | - | - | - | 84551 | 155870 | 14108 |

## 5.6 Experimental Design and Taguchi Analysis for Managerial Insights

Sensitivity analysis for integer models must be made by re-solving the problem which is a very time-consuming process. In addition, these resolving operations should be performed systematically. Therefore, at this stage of the study, since the sensitivity analysis cannot be applied directly to the mixed integer programming models and the results are not significant, Taguchi DOE approach is used in order to reach the optimum profit values and eco-indicator scores that are targeted and examine the effects of some parameters' values on the network design problem in a tire CLSC.

Genichi Taguchi came up with a solution which increases the efficiency of the evaluation and realization of experiments with the help of the approach called with his name (Ross, 1989). Besides being only an experimental design technique, Taguchi method is an extremely beneficial technique for high-quality system design. Moreover, it has been proven that the Taguchi experimental design is a method that can be used effectively in not only product development and process improvement studies but also designing and performance optimization of the high quality systems (Subulan and Tasan, 2011c; Subulan and Tasan, 2011d; Subulan and Cakmakci, 2012).

### *5.6.1 Determination of the Parameter (Factor) Levels and Appropriate Orthogonal Array*

Different scenarios are developed to find the controllable factors/parameters that have an impact on the total profit and eco-indicator 99 score of the CLSC network design. In these scenarios, returned rates, numbers of trucks of each type, incineration fraction for disposition of scrap tires and unit price of selling recycled materials for third party applications are determined as controllable factors. The parameter (factor) levels which have different measurements used in the Taguchi design are determined as follows in Table 5.13.

Table 5.13 Factor levels used in Taguchi design

| | **Number of vehicles for each type (unit)** | **Return rate (%)** | **Incineration fraction at disposal site (%)** | **Selling price of recycled materials ($)** |
|---|---|---|---|---|
| **Level 1** | 18 | %30 | %10 | -%50 |
| **Level 2** | - | %60 | %50 | +%20 |
| **Level 3** | 22 | %90 | %90 | +%50 |

For the experimental design that involves different levels of factors, since four factors with mixed levels (two or three) require at least 18 experiments and because of the total degrees of freedom is equal to 7, L18 orthogonal design matrix is used which has 17 degrees of freedom (17>7). Total CLSC profit and total eco-indicator score are determined as response variables for the Taguchi technique. Experimental results (value of response variables) obtained for each run and selected orthogonal array were shown in the table 5.14. In Table 5.13 and 5.14 positive values for selling price of recycled materials show increasing and negative values show decreasing in selling price in each run. Experiments are carried out using parameters defined at different levels and solution models generated in ILOG OPL Studio version 6.3. Fuzzy optimization results (preferred compromise solutions) which are provided at the end of the last iteration and satisfy the both profit and environmental oriented CLSC network are handled as experimental results.

Table 5.14 Orthogonal array of the experimental runs and response values

| Exp. no | Numbers of each vehicle type (unit) | Return rate (%) | Incineration fraction at disposal site (%) | Selling price of recycled materials ($) | Payoff matrix | | Fuzzy optimization results via interactive fuzzy goal programming | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | Total CLSC profit | Total eco-indicator score | Iteration no | Total CLSC profit | Total eco-indicator score | Auxiliary variable β |
| 1 | 18 | %30 | %10 | -%50 | 40696540 | 35217000 | 1 | 31867000 | 21268000 | 0.691663 |
| | | | | | 12061000 | 15049854 | 2 | 36245000 | 18563000 | 0.43503 |
| | | | | | | | 3 | 36289000 | 18559000 | 0.0010582 |
| 2 | 18 | %30 | %50 | +%20 | 46499166 | 46709000 | 1 | 39686000 | 21253000 | 0.802131 |
| | | | | | 12068000 | 14973549 | 2 | 39766000 | 20851000 | 0.012678 |
| | | | | | | | 3 | 40875000 | 19883000 | 0.164722 |
| 3 | 18 | %30 | %90 | +%50 | 52112033 | 46546000 | 1 | 42123000 | 22803000 | 0.750218 |
| | | | | | 12021000 | 14897505 | 2 | 43402000 | 21791000 | 0.12806 |
| | | | | | | | 3 | 45132000 | 20421000 | 0.19867 |
| 4 | 18 | %60 | %10 | -%50 | 40625849 | 35774000 | 1 | 18469000 | 15404000 | 0.710436 |
| | | | | | 11954000 | 15235160 | 2 | 19042000 | 15400000 | 0.025865 |
| | | | | | | | 3 | 19043000 | 15400000 | 0.000026 |
| 5 | 18 | %60 | %50 | +%20 | 46444160 | 47013000 | 1 | 38125000 | 22823000 | 0.759377 |
| | | | | | 11870000 | 15158449 | 2 | 40936000 | 20344000 | 0.323421 |
| | | | | | | | 3 | 41042000 | 20244000 | 0.019264 |
| 6 | 18 | %60 | %90 | +%50 | 52056600 | 46852000 | 1 | 39732000 | 24813000 | 0.693695 |
| | | | | | 11819000 | 15081018 | 2 | 44909000 | 20725000 | 0.420082 |
| | | | | | | | 3 | 45018000 | 20639000 | 0.015308 |

Table 5.14 Orthogonal array of the experimental runs and response values (Continues)

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| 7 | 18 | %90 | %10 | +%20 | 46417546 | 47106000 | 1 | 31705000 | 28888000 | 0.575026 |
| | | | | | 11797000 | 15423633 | 2 | 40784000 | 20579000 | 0.617098 |
| | | | | | | | 3 | 40888000 | 20484000 | 0.018447 |
| 8 | 18 | %90 | %50 | +%50 | 52031469 | 47314000 | 1 | 32010000 | 31214000 | 0.503621 |
| | | | | | 11696000 | 15345076 | 2 | 38713000 | 25901000 | 0.334813 |
| | | | | | | | 3 | 39957000 | 24915000 | 0.093379 |
| 9 | 18 | %90 | %90 | -%50 | 40469046 | 35608000 | 1 | 33331000 | 20362000 | 0.749483 |
| | | | | | 11711000 | 15266446 | 2 | 35952000 | 18878000 | 0.291210 |
| | | | | | | | 3 | 35981000 | 18870000 | 0.002154 |
| 10 | 22 | %30 | 10 | +%50 | 53336622 | 50451000 | 1 | 38020000 | 17225000 | 0.457806 |
| | | | | | 12170000 | 14883882 | 2 | 38025000 | 17224000 | 0.000324 |
| | | | | | | | 3 | - | - | - |
| 11 | 22 | %30 | %50 | -%50 | 41244301 | 37217000 | 1 | 31916000 | 21966000 | 0.679088 |
| | | | | | 12176000 | 14759019 | 2 | 35747000 | 19006000 | 0.410706 |
| | | | | | | | 3 | 37272000 | 18352000 | 0.154020 |
| 12 | 22 | %30 | %90 | +%20 | 47571658 | 50077000 | 1 | 34905000 | 27315000 | 0.643118 |
| | | | | | 12080000 | 14683431 | 2 | 42311000 | 19930000 | 0.584654 |
| | | | | | | | 3 | - | - | - |
| 13 | 22 | %60 | %10 | +%20 | 47623533 | 50755000 | 1 | 37081000 | 25593000 | 0.704140 |
| | | | | | 11989000 | 15020924 | 2 | 41228000 | 21434000 | 0.393351 |
| | | | | | | | 3 | - | - | - |

Table 5.14 Orthogonal array of the experimental runs and response values (Continues)

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| 14 | 22 | %60 | %50 | +%50 | 53230314 | 50557000 | 1 | 34016000 | 31519000 | 0.534584 |
| | | | | | 11947000 | 14945008 | 2 | 40386000 | 26024000 | 0.331540 |
| | | | | | | | 3 | 41754000 | 24844000 | 0.106471 |
| 15 | 22 | %60 | %90 | -%50 | 41133381 | 37467000 | 1 | 33077000 | 21100000 | 0.724269 |
| | | | | | 11915000 | 14868669 | 2 | 37179000 | 18549000 | 0.425210 |
| | | | | | | | 3 | - | - | - |
| 16 | 22 | %90 | %10 | +%50 | 53216395 | 51032000 | 1 | 32644000 | 32697000 | 0.504040 |
| | | | | | 11736000 | 15210894 | 2 | 38968000 | 27322000 | 0.307396 |
| | | | | | | | 3 | 44606000 | 22530000 | 0.395682 |
| 17 | 22 | %90 | %50 | -%50 | 41092777 | 37888000 | 1 | 35685000 | 20966000 | 0.743704 |
| | | | | | 11710000 | 15133749 | 2 | 37366000 | 19153000 | 0.310847 |
| | | | | | | | 3 | 37367000 | 19152000 | 0.000526 |
| 18 | 22 | %90 | %90 | +%20 | 47455713 | 50647000 | 1 | 38330000 | 24134000 | 0.744949 |
| | | | | | 11674000 | 15056308 | 2 | 42018000 | 20466000 | 0.404058 |

It is assumed that the DM accepted the solution obtained by the second or third iteration as the preferred compromise solution. In the first phase of the experimental analysis, it is assumed that there are no interactions between the controllable factors which may affect the performance characteristics significantly. In the later evaluations, possible factor interactions will be examined with the help of interaction graphs.

### *5.6.2 Analysis of the Experimental Results*

For the evaluation of experimental results and effects of related factors, Taguchi's signal/noise (S/N) ratios, analysis of means graphs, interaction graphs and analysis of variance (ANOVA) are used and experiments are carried out in MINITAB 14 according to Taguchi L18 scheme.

Table 5.15 Corresponding S/N ratios of Taguchi experimental results

| Exp. no | Y1-Total CLSC profit (dB) | Y2-Total eco-indicator score (dB) | Y3-Total CLSC profit (dB) | Y4-Total eco-indicator score (dB) |
|---|---|---|---|---|
| 1 | -152,191 | -143,551 | -151,196 | -145,371 |
| 2 | -153,349 | -143,506 | -152,229 | -145,97 |
| 3 | -154,339 | -143,462 | -153,09 | -146,202 |
| 4 | -152,176 | -143,657 | -145,595 | -143,75 |
| 5 | -153,339 | -143,613 | -152,265 | -146,126 |
| 6 | -154,33 | -143,569 | -153,068 | -146,294 |
| 7 | -153,334 | -143,764 | -152,232 | -146,228 |
| 8 | -154,325 | -143,719 | -152,032 | -147,929 |
| 9 | -152,142 | -143,675 | -151,121 | -145,515 |
| 10 | -154,541 | -143,454 | -151,601 | -144,723 |
| 11 | -152,307 | -143,381 | -151,428 | -145,274 |
| 12 | -153,547 | -143,337 | -152,529 | -145,99 |
| 13 | -153,556 | -143,534 | -152,304 | -146,622 |
| 14 | -154,523 | -143,49 | -152,414 | -147,904 |
| 15 | -152,284 | -143,445 | -151,406 | -145,366 |
| 16 | -154,521 | -143,643 | -152,988 | -147,055 |
| 17 | -152,275 | -143,599 | -151,45 | -145,644 |
| 18 | -153,526 | -143,554 | -152,469 | -146,221 |

In Table 5.15, Y1 and Y2 represent the optimization results of the deterministic model that consider the two goals independently (Case 1). However, Y3 and Y4 indicate the fuzzy optimization results which consider these objectives simultaneously (Case 2).

Later, in order to clarify how these selected parameters affect the two performance criteria mentioned before as total CLSC profit and total eco-indicator 99 score, the statistical analysis was carried out. These main-factor effects obtained from the statistical analysis of means and S/N ratios are plotted in Figure 5.27, 5.28, 5.29 and 5.30 for case-1. In addition response tables for means and S/N ratios are provided in Tables 5.16, 5.17, 5.18 and 5.19.

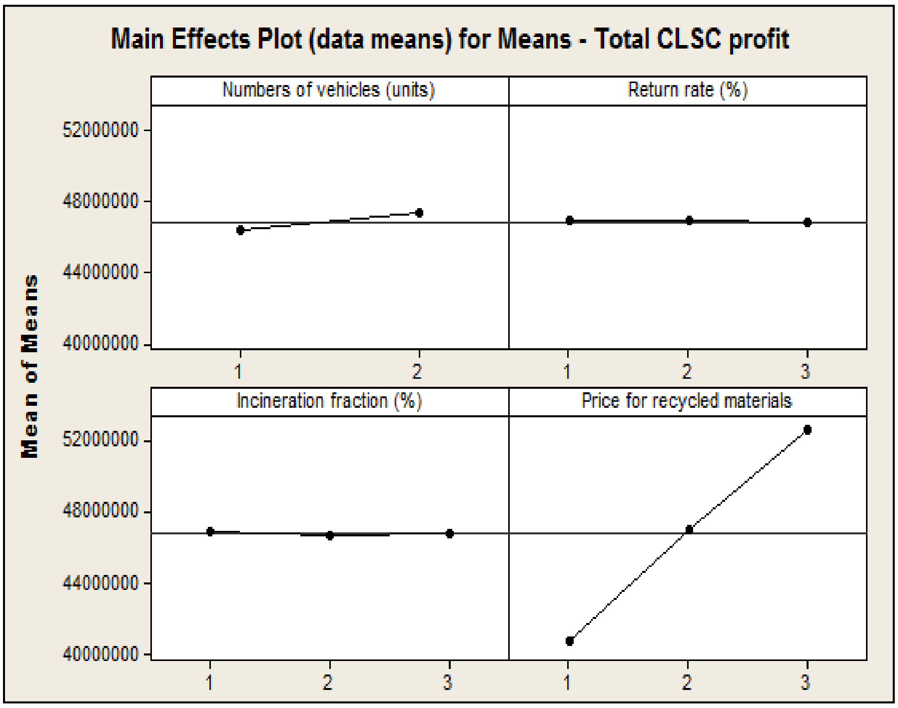



Figure 5.27 The main factor effects obtained from statistical analysis of means for total CLSC profit in case-1

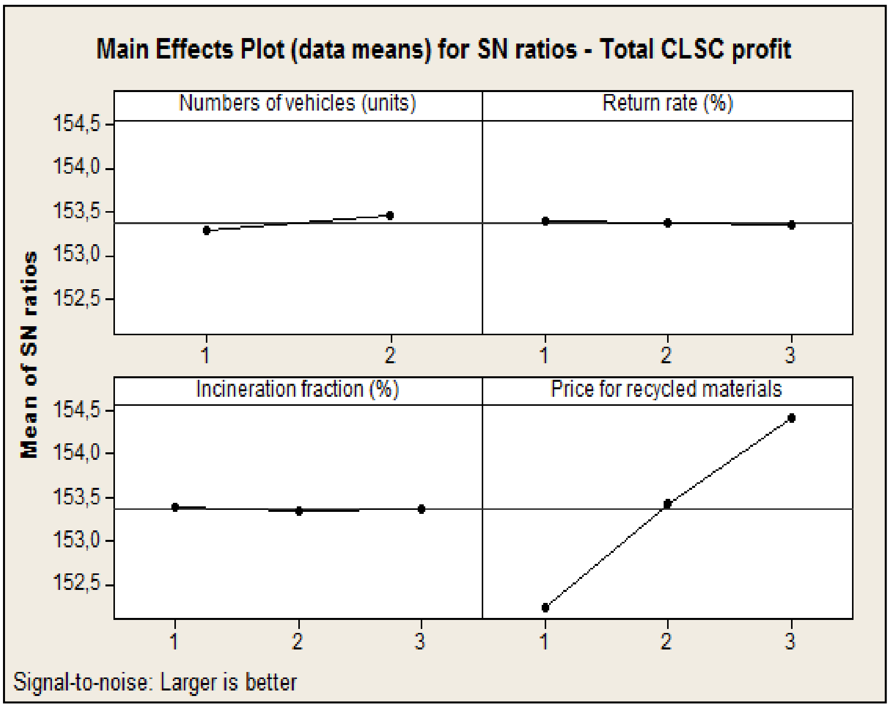



Figure 5.28The main factor effects obtained from S/N ratios for total CLSC profit in case-1

According to Figures 5.27 and 5.28, except the selling price of recycled materials, all other factors are not important for the performance criterion since they do not cause significant variability or wide variations on the total CLSC profit as a response variable. However, when we examine the effects of these factors on environment, all of the factors have a significant impact except price of recycled materials. For instance, when the numbers of vehicles are equal to minimum level (18 trucks), return rate is equal to maximum level (%90) and incineration rate for disposition is equal to minimum level (%10), total eco-indicator score along the CLSC will increase in the case of considering performance characteristics independently.

For finalizing the optimization phase, variation analysis is performed using the calculated signal/noise ratios. In other words, to verify these results, Taguchi’s S/N ratios were used. Larger and smaller is better categories were selected while calculating the S/N ratios for total CLSC profit and eco-indicator score, respectively.

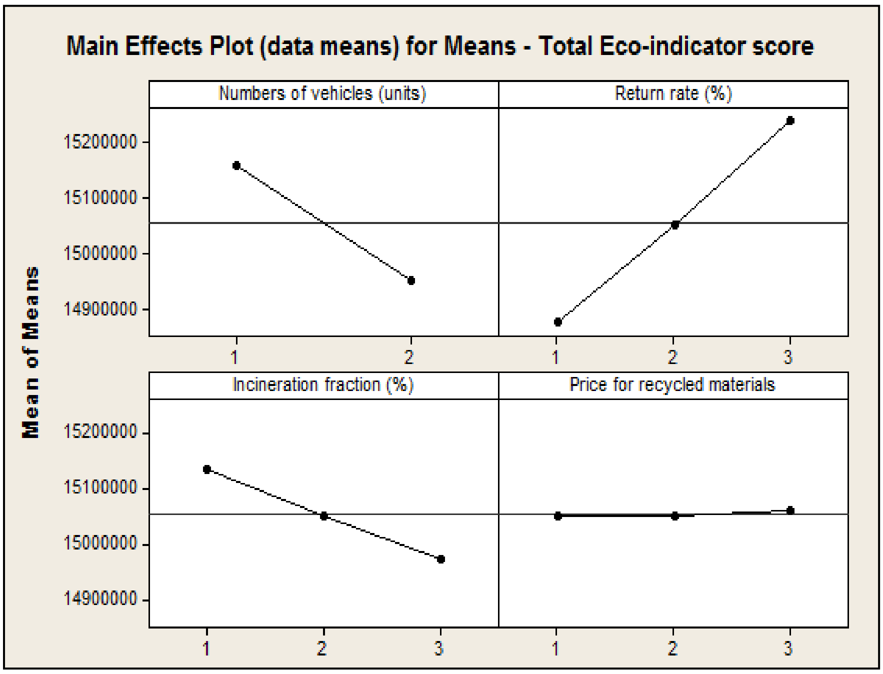



Figure 5.29 The main factor effects obtained from statistical analysis of means for total eco indicator 99 score in case-1

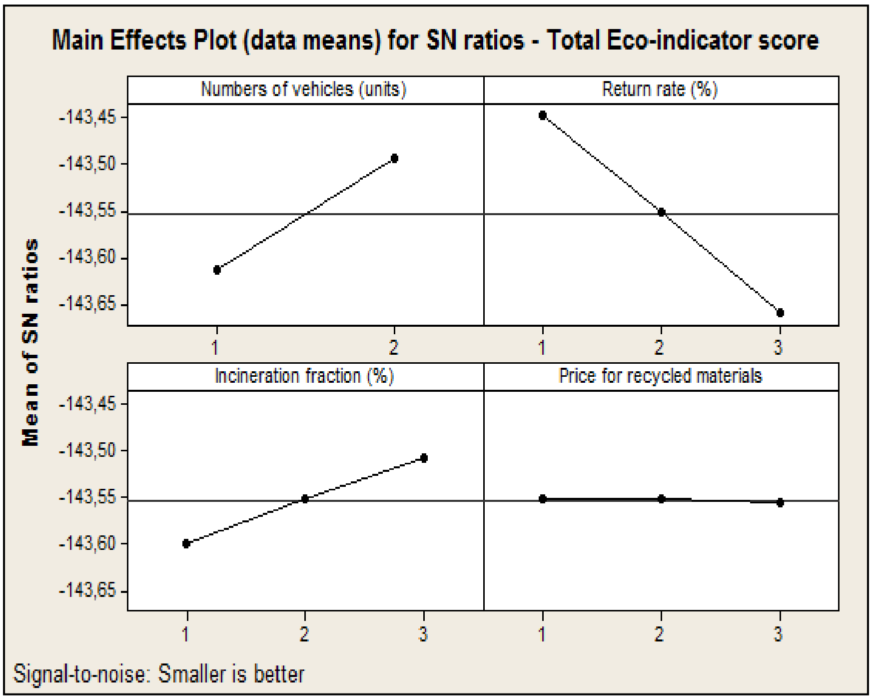



Figure 5.30 The main factor effects obtained from S/N ratios for total eco-indicator 99 score in case-1

Table 5.16 Response table for S/N ratios (Total Profit) in case-1

| Response table for S/N ratios (Total profit – Larger is better) | | | | |
|---|---|---|---|---|
| **Level** | **Numbers of vehicles** | **Return rate** | **Incineration fraction** | **Price for recycled materials** |
| 1 | 153.3 | 153.4 | 153.4 | 152.2 |
| 2 | 153.5 | 153.4 | 153.4 | 153.4 |
| 3 | - | 153.4 | 153.4 | 154.4 |
| Delta | 0.2 | 0 | 0 | 2.2 |
| Rank | 2 | 4 | 3 | 1 |

Table 5.17 Response table for S/N ratios (Total Eco-indicator Score) in case-1

| Response table for S/N ratios (Total eco-indicator score – smaller is better) | | | | |
|---|---|---|---|---|
| **Level** | **Numbers of vehicles** | **Return rate** | **Incineration fraction** | **Price for recycled materials** |
| 1 | -146.6 | -143.4 | -143.6 | -143.6 |
| 2 | -143.5 | -143.6 | -143.6 | -143.6 |
| 3 | - | -143.7 | -143.5 | -143.6 |
| Delta | 0.1 | 0.2 | 0.1 | 0 |
| Rank | 2 | 1 | 3 | 4 |

Table 5.18 Response table for means (Total Profit) in case-1

| Response table for means (Total profit ) | | | | |
|---|---|---|---|---|
| **Level** | **Numbers of vehicles** | **Return rate** | **Incineration fraction** | **Price for recycled materials** |
| 1 | 46372490 | 46910053 | 46986081 | 40876982 |
| 2 | 47322744 | 46852306 | 46757031 | 47001963 |
| 3 | - | 46780491 | 46799739 | 52663906 |
| Delta | 950254 | 129562 | 229050 | 11786923 |
| Rank | 2 | 4 | 3 | 1 |

Table 5.19 Response table for means (Total Eco-indicator Score) in case-1

| **Response table for means (Total eco-indicator)** | | | | |
|---|---|---|---|---|
| **Level** | **Numbers of vehicles** | **Return rate** | **Incineration fraction** | **Price for recycled materials** |
| 1 | 15158966 | 14874540 | 15137391 | 15052150 |
| 2 | 14951320 | 15051538 | 15052475 | 15052716 |
| 3 | - | 15239351 | 14975563 | 15060564 |
| Delta | 207645 | 364811 | 161828 | 8414 |
| Rank | 2 | 1 | 3 | 4 |

Because, objectives of this Chapter are maximizing the total profit and minimizing the environmental impact of the CLSC. In the result of all these S/N calculations, the highest S/N ratio value refers to the best experiment results. In other words, it refers to the experimental results where the total profit of the CLSC network design problem is maximum and total environmental impact is minimum.

According to the calculated S/N ratios, main factor levels; numbers of vehicles-2, return rate-1, 2, 3, incineration fraction-1, 2, 3 and selling price of recycled materials-3 are observed as the factor levels increasing the total profit in case-1. Furthermore, main effect plots for means represent that numbers of vehicles-2, return rate-1, incineration fraction-3 and selling price for recycled materials-1,2,3 are determined as factor levels reducing the environmental impact along the CLSC in case-1. It is obviously seen that, the main factor effects with analysis of means graphs and the S/N ratios supported the same optimal factor levels.

As it can be seen in response tables (Tables 5.16, 5.17, 5.18 and 5.19), two of the most effectual factors are price for recyced materials and numbers of vehicles for total CLSC profit since these factors have the largest delta value. Similarly, return rate and numbers of vehicles have largest effect on the environment in case-1. These results are also supported by the outputs of analysis of variance depicted in Table 5.20 for case-1.

Table 5.20 ANOVA results for case-1

**General Linear Model: Y1 (Total CL; Y2 (Total Ec versus Numbers of v; Return ra**

| Factor | Type | Levels | Values |
|---|---|---|---|
| Numbers of vehicles (units) | fixed | 2 | 1; 2 |
| Return rate (%) | fixed | 3 | 1; 2; 3 |
| Incineration fraction (%) | fixed | 3 | 1; 2; 3 |
| Price for recycled materials | fixed | 3 | 1; 2; 3 |

**Analysis of Variance for Y1 (Total CLSC profit), using Adjusted SS for Tests**

| Source | DF | Seq SS | Adj SS | Adj MS | F | P |
|---|---|---|---|---|---|---|
| Numbers of vehicles (units) | 1 | 4,06342E+12 | 4,06342E+12 | 4,06342E+12 | 212,16 | 0,000 |
| Return rate (%) | 2 | 50557103280 | 50557103280 | 25278551640 | 1,32 | 0,310 |
| Incineration fraction (%) | 2 | 1,78022E+11 | 1,78022E+11 | 89011131313 | 4,65 | 0,037 |
| Price for recycled materials | 2 | 4,17009E+14 | 4,17009E+14 | 2,08505E+14 | 10886,69 | 0,000 |
| Error | 10 | 1,91522E+11 | 1,91522E+11 | 19152248947 | | |
| Total | 17 | 4,21493E+14 | | | | |

S = 138392   R-Sq = 99,95%   R-Sq(adj) = 99,92%

**Analysis of Variance for Y2 (Total Eco-indicator score), using Adjusted SS for Tests**

| Source | DF | Seq SS | Adj SS | Adj MS | F | P |
|---|---|---|---|---|---|---|
| Numbers of vehicles (units) | 1 | 1,94024E+11 | 1,94024E+11 | 1,94024E+11 | 1641,00 | 0,000 |
| Return rate (%) | 2 | 3,99378E+11 | 3,99378E+11 | 1,99689E+11 | 1688,91 | 0,000 |
| Incineration fraction (%) | 2 | 78629292424 | 78629292424 | 39314646212 | 332,51 | 0,000 |
| Price for recycled materials | 2 | 265430540 | 265430540 | 132715270 | 1,12 | 0,363 |
| Error | 10 | 1182352004 | 1182352004 | 118235200 | | |
| Total | 17 | 6,73479E+11 | | | | |

S = 10873,6   R-Sq = 99,82%   R-Sq(adj) = 99,70%

Since the p-values of some factors (numbers of vehicles and price of recycled materials) in ANOVA table are zero and $p \leq \alpha = 0{,}01$ or $0{,}05$ (confidence interval) for total CLSC profit, we can say that the $H_0$ hypothesis will be rejected. In the other words, these factors have an impact on the corresponding performance criterion. Similary, for the other performance criterion (total eco-indicator score), except the selling price of recycled materials, all other factors have zero p-value and affect the environmental performance.

When we examine the interactions between each factor which affect the total profit of the CLSC in Figures 5.31 and 5.32, there are no strong interactions between any two factors except these factor pairs (numbers of vehicles-incineration fraction; return rate-incineration fraction) since the interaction lines are parallel or overlapped.

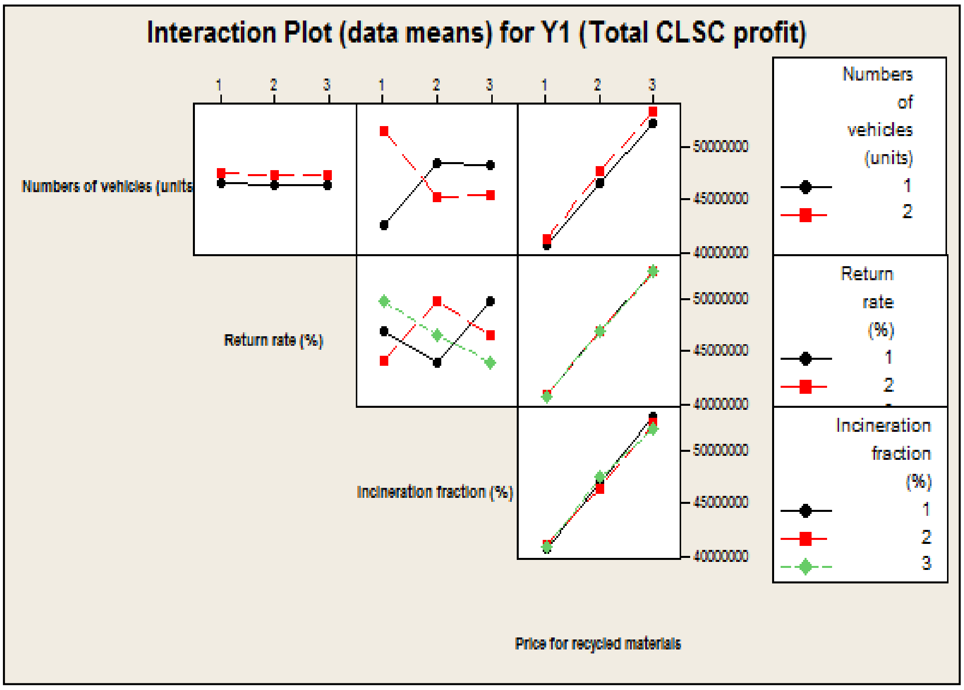



Figure 5.31 Interaction graph for total CLSC profit in case-1

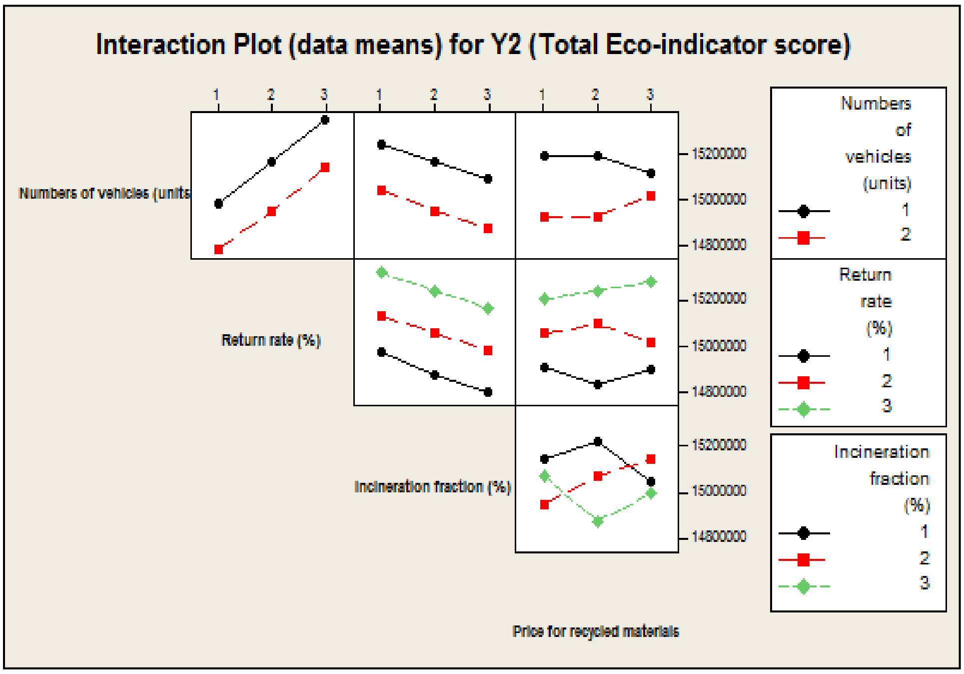



Figure 5.32 Interaction graph for total eco-indicator score in case-1

For instance, let examine the interaction between return rate and incineration fraction in terms of profit as a performance measurement. It is obviously seen that total CLSC profit will decrease in the case of increasing the return rate and incineration fraction simultaneously. On the other hand, when the return rate increases up to the maximum level without any change in incineration fraction, total profit will also increase.

However, when we examine the factor interactions in terms of environmental performance, it is obviously seen that there is a weak interaction between these pairs (return rate-price of recycled materials; numbers of vehicles-price of recycled materials). In addition, there is a strong interaction between incineration fraction and price of recycled materials.

For case-2, statistical analysis of means and S/N ratios are also conducted as shown in Figures 5.33, 5.34, 5.35 and 5.36. Moreover, response tables are also depicted in Tables 5.21, 5.22, 5.23 and 5.24 for both performance criteria.

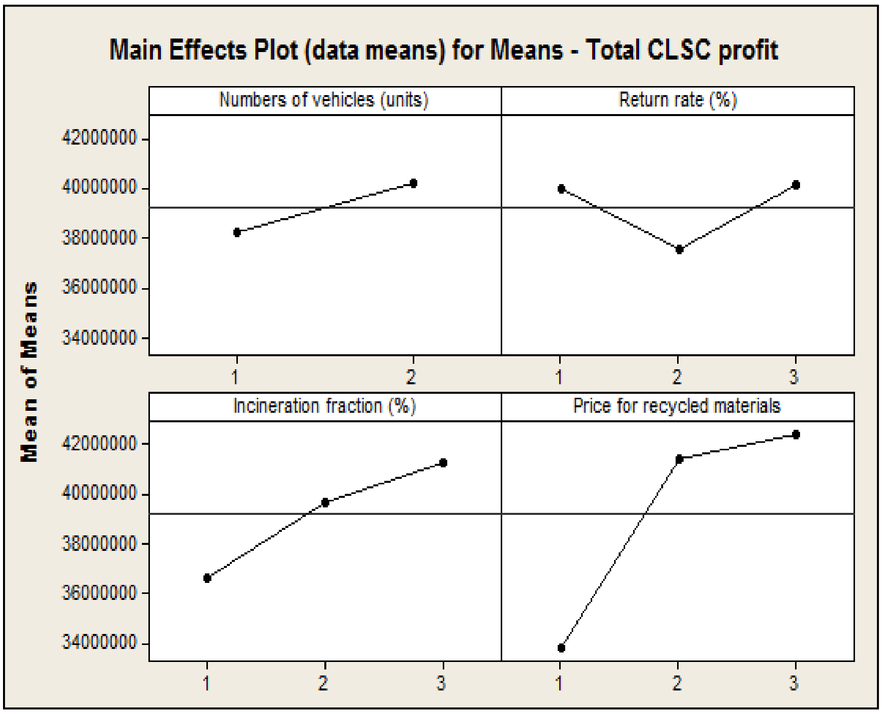



Figure 5.33 The main factor effects obtained from statistical analysis of means for total CLSC profit in case-2

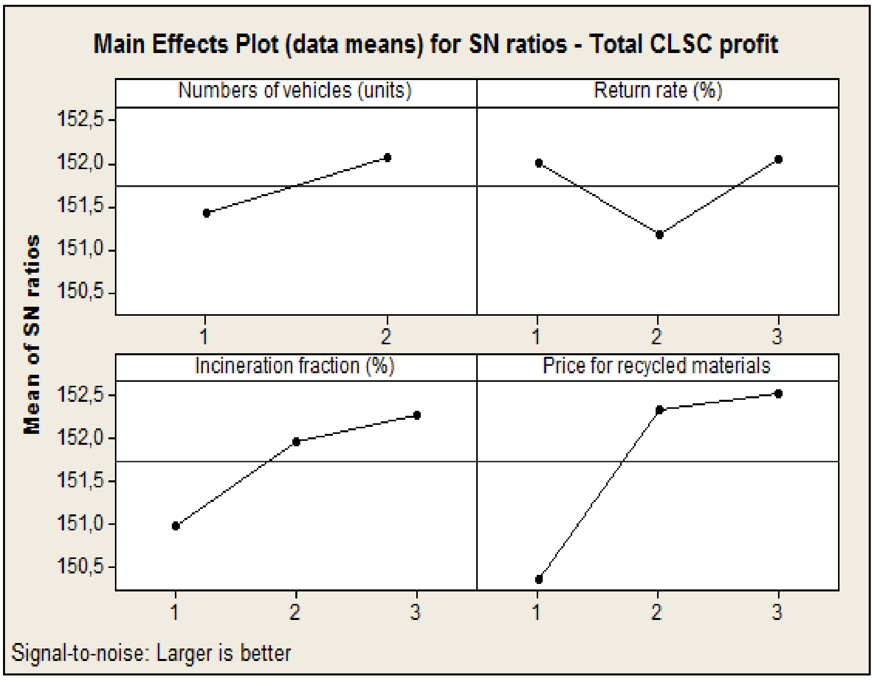



Figure 5.34The main factor effects obtained from S/N ratios for total CLSC profit in case-2

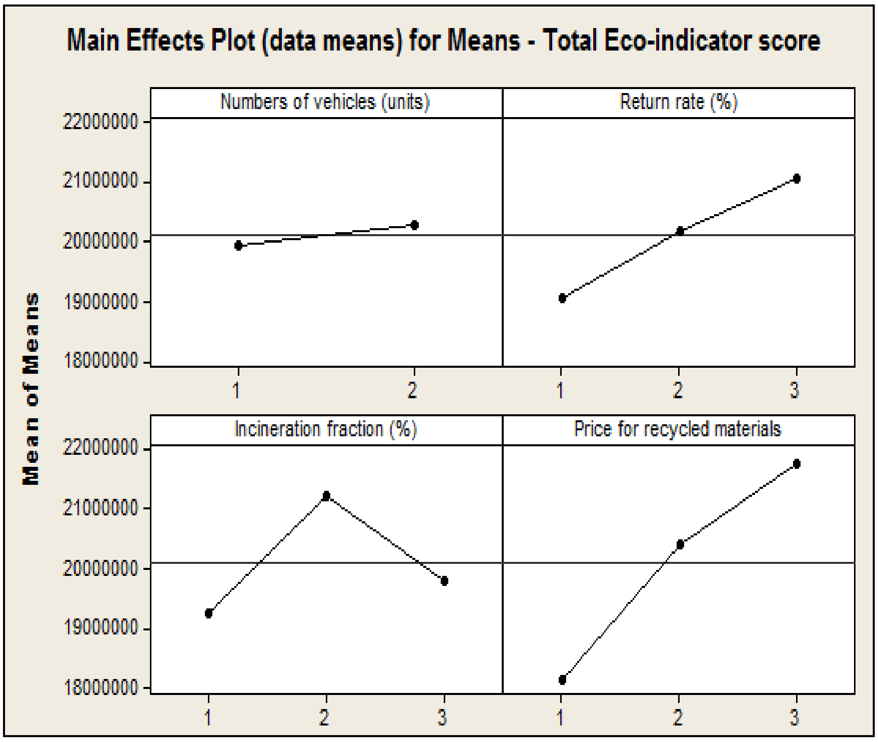



Figure 5.35 The main factor effects obtained from statistical analysis of means for total eco-indicator 99 score in case-2

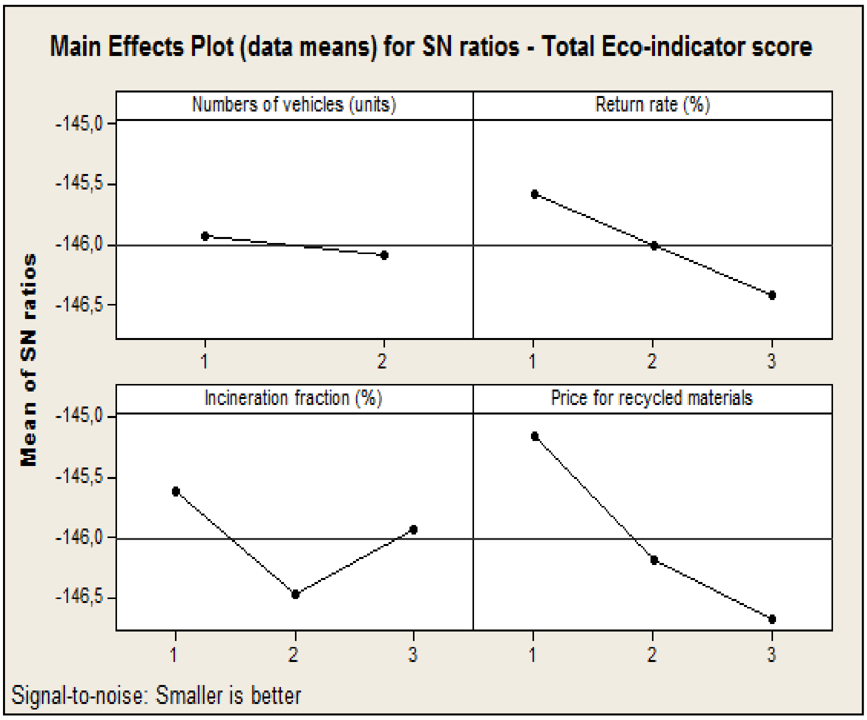



Figure 5.36 The main factor effects obtained from S/N ratios for total eco-indicator 99 score in case-2

According to the above figures which display the main factor effects, when we take into account these objectives simultaneously via the interactive fuzzy goal programming approach, factor effects will become more apparent.

In this case, numbers of vehicles-2; return rate-1, 3; incineration fraction-3 and price of recycled materials-3 are observed as the factor levels increasing the total profit. Similarly, numbers of vehicles-1, return rate-1, incineration fraction-1 and price for recycled materials-1 are determined as the factor levels reducing the environmental impact.

Tables from 5.21 to 5.25 also show that price of recycled materials and incineration fraction are the most important factors for both total profit and total eco-indicator score since they have the largest delta value. Although the obtained general linear model has not a sufficient coefficient of determination value (R-Sq) for its explanatory power, ANOVA results also reveal that price of recycled materials has the greatest impact on the all performance criteria. In other words, obtained general linear model does not fit the data extremely well in case-2.

Table 5.21 Response table for S/N ratios (Total Profit) in case-2

| **Response table for S/N ratios (Total profit – Larger is better)** | | | | |
|---|---|---|---|---|
| **Level** | **Numbers of vehicles** | **Return rate** | **Incineration fraction** | **Price for recycled materials** |
| 1 | 151.4 | 152.0 | 151.0 | 150.4 |
| 2 | 152.1 | 151.2 | 152.0 | 152.3 |
| 3 | - | 152.0 | 152.3 | 152.5 |
| Delta | 0.6 | 0.9 | 1.3 | 2.2 |
| Rank | 4 | 3 | 2 | 1 |

Table 5.22 Response table for S/N ratios (Total Eco-indicator Score) in case-2

| **Response table for S/N ratios (Total eco-indicator score – smaller is better)** | | | | |
|---|---|---|---|---|
| **Level** | **Numbers of vehicles** | **Return rate** | **Incineration fraction** | **Price for recycled materials** |
| 1 | -145.9 | -145.6 | -145.6 | -145.2 |
| 2 | -146.1 | -146.0 | -146.5 | -146.2 |
| 3 | - | -146.4 | -145.9 | -146.7 |
| Delta | 0.2 | 0.8 | 0.8 | 1.5 |
| Rank | 4 | 3 | 2 | 1 |

Table 5.23 Response table for means (Total Profit) in case-2

| **Response table for means (Total profit )** | | | | |
|---|---|---|---|---|
| **Level** | **Numbers of vehicles** | **Return rate** | **Incineration fraction** | **Price for recycled materials** |
| 1 | 38247222 | 39984000 | 36679833 | 33855167 |
| 2 | 40195556 | 37544000 | 39711167 | 41393667 |
| 3 | - | 40136167 | 41273167 | 42415333 |
| Delta | 1948333 | 2592167 | 4593333 | 8560167 |
| Rank | 4 | 3 | 2 | 1 |

Table 5.24 Response table for means (Total Eco-indicator Score) in case-2

| Response table for means (Total eco-indicator) | | | | |
|---|---|---|---|---|
| **Level** | **Numbers of vehicles** | **Return rate** | **Incineration fraction** | **Price for recycled materials** |
| 1 | 19935000 | 19061500 | 19271833 | 18147000 |
| 2 | 20275667 | 20185000 | 21231667 | 20406833 |
| 3 | - | 21069500 | 19812500 | 21762167 |
| Delta | 340667 | 2008000 | 1959833 | 3615167 |
| Rank | 4 | 2 | 3 | 1 |

Table 5.25 ANOVA results for case-2

**General Linear Model: Y3 (Total CL; Y4 (Total Ec versus Numbers of v; Return ra**

```
Factor                        Type   Levels  Values
Numbers of vehicles (units)   fixed       2  1; 2
Return rate (%)               fixed       3  1; 2; 3
Incineration fraction (%)     fixed       3  1; 2; 3
Price for recycled materials  fixed       3  1; 2; 3

Analysis of Variance for Y3 (Total CLSC profit), using Adjusted SS for Tests

Source                        DF       Seq SS       Adj SS       Adj MS     F      P
Numbers of vehicles (units)    1  1,70820E+13  1,70820E+13  1,70820E+13  0,84  0,381
Return rate (%)                2  2,53922E+13  2,53922E+13  1,26961E+13  0,62  0,556
Incineration fraction (%)      2  6,54551E+13  6,54551E+13  3,27275E+13  1,61  0,248
Price for recycled materials   2  2,62298E+14  2,62298E+14  1,31149E+14  6,44  0,016
Error                         10  2,03585E+14  2,03585E+14  2,03585E+13
Total                         17  5,73813E+14

S = 4512044   R-Sq = 64,52%   R-Sq(adj) = 39,69%
R denotes an observation with a large standardized residual.

Analysis of Variance for Y4 (Total Eco-indicator score), using Adjusted SS for
     Tests
Source                        DF       Seq SS       Adj SS       Adj MS     F      P
Numbers of vehicles (units)    1  5,22242E+11  5,22242E+11  5,22242E+11  0,18   0,684
Return rate (%)                2  1,21533E+13  1,21533E+13  6,07666E+12  2,04   0,180
Incineration fraction (%)      2  1,22946E+13  1,22946E+13  6,14730E+12  2,07   0,177
Price for recycled materials   2  4,00264E+13  4,00264E+13  2,00132E+13  6,73   0,014
Error                         10  2,97576E+13  2,97576E+13  2,97576E+12
Total                         17  9,47542E+13
S = 1725039   R-Sq = 68,59%   R-Sq(adj) = 46,61%
```

In Figures 5.37 and 5.38, we can see the interactions between each factor which affects the total CLSC profit and environmental performance.

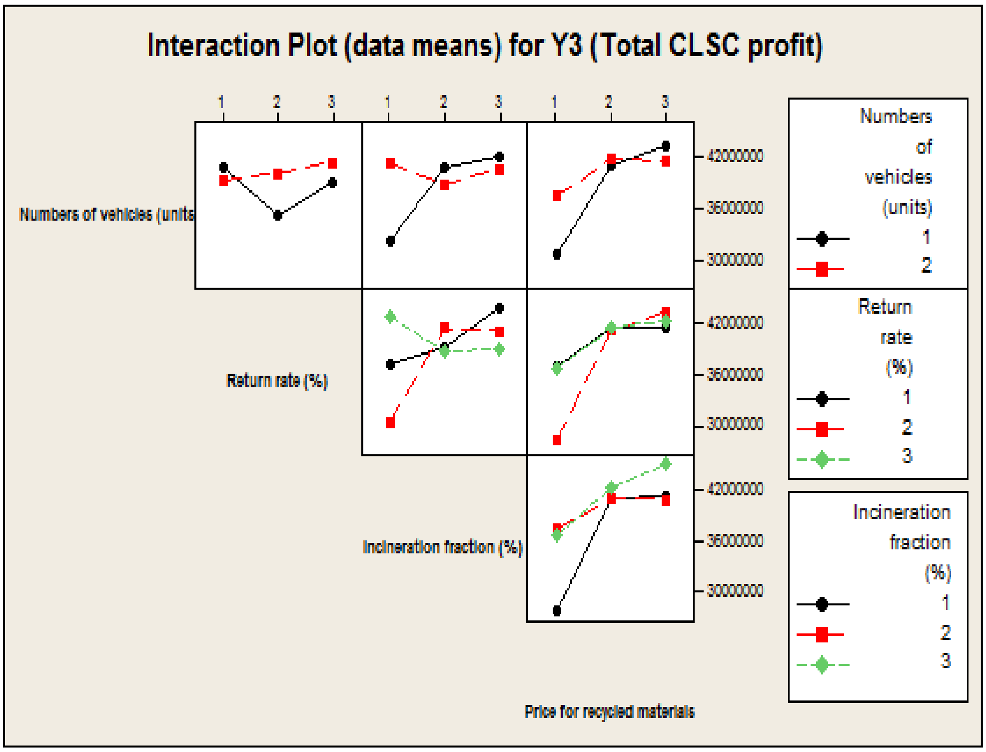



Figure 5.37 Interaction graph for total CLSC profit in case-2

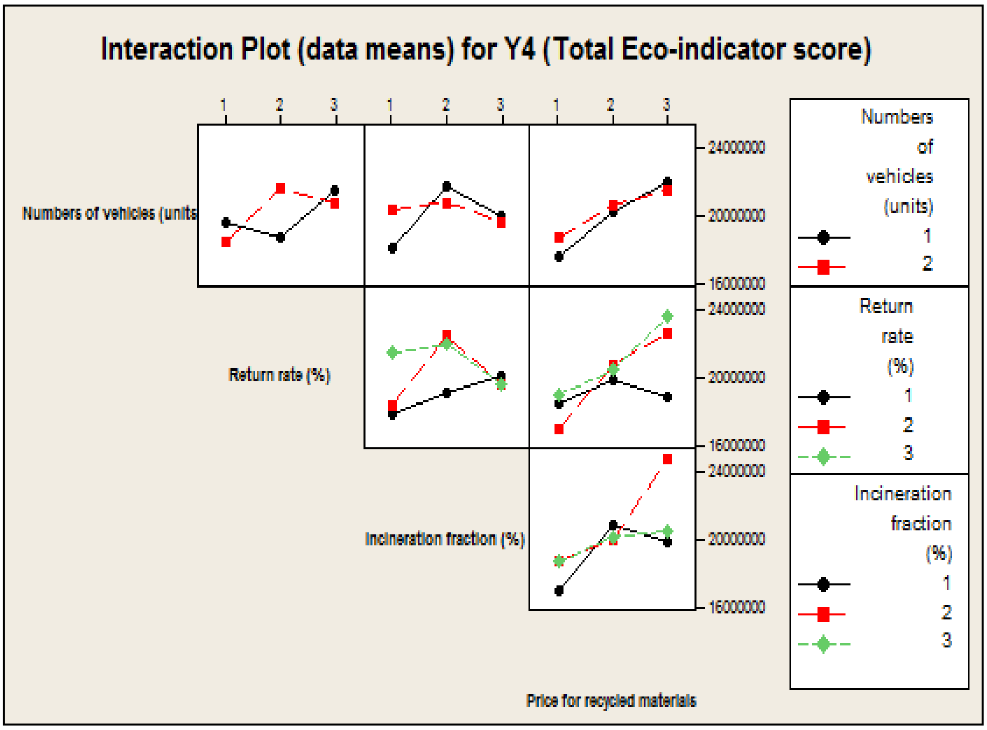



Figure 5.38 Interaction graph for total eco-indicator score in case-2

There are strong or close to strong interactions between all factors. For instance, when the numbers of vehicles and return rate are increased simultaneously, total profit also will increase. Similarly, decreasing in numbers of vehicles and decreasing in price of recycled materials yield more environmental friendly configuration. Because, the lower price of recycled materials, the less quantity of sales to the third party applications. Therefore, more recycled materials can be used in the new tire production.

## 5.7 Chapter Conclusion and Future Research

In order to reach the maximum profit and minimum environmental impact, the best factor-level combinations obtained from the above computational experiments are given in Table 5.26 for both case-1 and 2. The comprimise factor levels which are common for all cases and performance criteria are determined as numbers of vehicles-2, return rate-1, incineration fraction-3 and price of recycled materials-3.

Table 5.26 Optimal setting showing results for total CLSC profit and eco-indicator score

| Factors | Best factor levels for total CLSC profit | | Best factor levels for total eco-indicator score | |
|---|---|---|---|---|
| | **Case-1** | **Case-2** | **Case-1** | **Case-2** |
| Numbers of vehicles | 2 | 2 | 2 | 1 |
| Return rate | 1,2,3 | 1,3 | 1 | 1 |
| Incineration fraction | 1,2,3 | 3 | 3 | 1 |
| Selling price of recycled materials | 3 | 3 | 1,2,3 | 1 |

In addition, since full factorial design is not performed in this Chapter, all of the factor level combinations are not available in the selected orthogonal array (Table 5.14). Thus, the proposed model should be re-solved with the selected factor levels for the confirmation run. When the confirmation run is conducted in ILOG OPL Studio version 6.3 with these compromise factor levels which integrate the results of both case-1 and 2, the following total profit value and eco-indicator score are obtained as shown in Table 5.27.

Table 5.27 Results of the confirmation run

| **Factors** | **Value** | **Payoff matrix** | | **Fuzzy optimization results** | | | |
|---|---|---|---|---|---|---|---|
| | | Total profit | Total eco-indicator score | Total profit | Total eco-indicator score | Auxiliary variable β | Solving time (sec.) |
| Numbers of vehicles | 22 | $53227967 | 50023000 | 31615000 | 33246000 | 0.474750 | 999.84 |
| | | | | 39888000 | 26141000 | 0.382782 | 336.50 |
| Return rate | %30 | | | 43768000 | 22809000 | 0.290835 | 44.96 |
| Incineration fraction | %90 | | | **44332000** | **22325000** | **0.059622** | **4522.3** |
| | | $12080000 | 14683432 | | | | |
| Selling price of recycled materials | +%50 | | | | | | |

In summary, a multi-objective, multi-product, multi echelon and multi period sustainable network design model is developed for a tire CLSC while taking into account the different recovery alternatives simultaneously, recycling, energy recovery and remanufacturing. The proposed model is illustrated and tested through an example inspired from tire industry case in Aegean region of Turkey.

Above mentioned characteristics in section 3.4 and features differentiate this proposed model from the current ones in the relevant literature. In deterministic condition, assessment and measurement of total environmental damage by eco-indicator 99 methodology is a challenging task and some information can be incomplete or unobtainable for the environmental impact parameters. For this reason, besides these environmental parameters, uncertainty related to the demand of new and retreaded tires, return quantities of the end of life tires, return rates and capacities (for both facilities and vehicles) may be overcome by employing fuzzy mathematical programming approach in the future researches.

# CHAPTER SIX
# FUZZY MIXED INTEGER PROGRAMMING MODEL FOR MEDIUM-TERM PLANNING IN A CLOSED-LOOP SUPPLY CHAIN WITH REMANUFACTURING OPTION

## 6.1 Introduction

As mentioned in background section 1.1, increased environmental and economical issues related to the discarded products and legal regulations generated by the governments have been putting pressure on many producers about the production, collection, recovery and disposition of the products in an environmentally conscious manner. In addition to the environmental factors and laws, many companies and organizations are aware of the revenue obtained from the product recovery for their sustainability. Therefore, RL activities, efficient strategic and tactical planning processes of CLSCs and product recovery systems have been much more interested issues throughout this decade.

Due to this fact, companies should take into account the utilized recovery option such as recycling, remanufacturing etc. while preparing their Medium-Term Planning (MTP) processes instead of using traditional production planning or reverse supply chain planning models. Thus, an integrated planning process for CLSCs namely medium-term planning is required in tactical level. With the ongoing development of these recovery concepts, integration of these issues into the MTP processes of the CLSC in which they are involved is required for the enterprise firms in order to obtain sustainable competitive advantage. With this integration, a global production plan that generates the production/remanufacturing, distribution and inventory schedule for all companies in the supply chain is provided (Zuluaga and Lourenco, 2002). In addition, effective and efficient management of CLSCs can be provided with the inclusion of remanufacturing option that is a main subject of this Chapter in the developed tactical planning model. These also yields cost savings especially in production, remanufacturing, collection, disposal, inventory and transportation.

Shi, Zhang, and Sha (2011) emphasized that when manufacturing and remanufacturing operations are included in the CLSC planning, the coordination between them is a crucial task to the manufacturer.

Looking from the perspective of planning for businesses, there are mainly three different levels of planning which depend on the length of planning period in the production systems: (1) Long term planning (strategic) (2) Medium term planning (tactical) (3) Short term planning (Operative) (Zuluaga and Lourenco, 2002). Additionally, it is emphasized by Nukala and Gupta (2006) that strategic, tactical and operational planning are the three important stages of planning in a supply chain. After the RL & CLSC network design problem which is strategically important, MTP problem of the supply chain emerged in the tactical level. Also, the traditional production planning models which are developed for individual elements of the supply chains are not enough for the companies which operate in the global competitive markets.

In this Chapter, a fuzzy mixed integer programming model for MTP problem in the CLSC of a conceptual product is developed based on the studies of Kreipl and Pinedo (2004), Pinedo (2005) which were developed for traditional forward supply chains. Since the proposed model includes both forward and reverse flows, it is called as an integrated model (Dolgui, Soldek, and Zaikin, 2005). Furthermore, in contrast to the traditional production planning, MTP models attempt to optimize all of the consecutive stages in the supply chains (Kreipl and Pinedo, 2004) and also CLSCs. Therefore, the objective function of the developed MTP model may be explained as follows; minimize the total costs of the CLSC that involve production costs, inventory carrying costs, transportation costs, remanufacturing costs, collection costs, disposal costs, tardiness costs and the penalty costs for non-deliveries.

While developing the mathematical model, one of the most commonly encountered product recovery option 'remanufacturing' is discussed as mentioned earlier. Kim, Song, Kim, and Jeong (2006) defined remanufacturing as "an industrial process in which worn-out products are restored to like-new condition". In addition; according to Sasikumar, Kannan, and Haq (2010), the aim of remanufacturing is "to bring the old or used product into as new conditions by performing the required disassembly, overhaul, and replacement operations". Based on these definitions, remanufacturing of returned products in the right quantities, at the right time and at the right facilities will be one of the main goal of MTP process to represent the right type and amounts of remanufactured products to the end customers.

After solving the proposed fuzzy mathematical model, following decisions can be yielded:

- Production/remanufacturing quantities for all types of products at each manufacturing plant and remanufacturing facility.
- Assignment of both manufactured/remanufactured of products to the various manufacturing plants/remanufacturing facilities in each planning period.
- Allocation of resources to the various product families.
- Inventory levels of finished goods at the manufacturing plants.
- Inventory levels of both newly manufactured/remanufactured products in the wholesalers.
- Inventory levels of returned products at the collection centers and wholesalers.
- Inventory levels of both used and remanufactured products at the remanufacturing facilities.
- Returned quantities of used products through different ways such as through the collection centers or wholesalers.
- Backordering or non-delivering levels of products in each time period for the wholesalers' and retailers' demands.
- Finally, transportation quantities between different tiers in the CLSC network.

Real world CLSCs are surrounded with uncertainty. Uncertainty associated with the amounts of customers' demand and accordingly return rate are major problems in both RL & CLSC planning. In addition, uncertainty related to the conformity rate/acceptance ratio for the remanufacturing operation should be taken into account while considering uncertainty regarding return rate. Because, timing, quantity and also quality specification rate of returned products involve fuzziness. Therefore, unlike the other studies in the literature, both of the return rate and acceptance rate are considered as fuzzy in the scope of this Chapter. Furthermore, since the crisp demand is not realistic and does not exactly equal to the forecasted demand, uncertain demand is considered which makes the model more realistic for the industrial applications. Also, all of the capacity constraints such as storage capacities, upper bounds on transportation quantities, total weekly available time for both production/remanufacturing and the aspiration level of the objective function are considered as fuzzy.

The proposed fuzzy mathematical program is converted into a crisp equivalent by employing the well known aggregation operators that were proposed by different authors in the literature (Belman and Zadeh, 1970), (Zimmermann, 1996), (Werner, 1987) and (Li, 1990). Additionally, fuzzy structure of some non-linear constraints in the proposed model is overcome with the simultaneous consideration of transformation of these constraints into the linear form and converting them into a crisp equivalent.

In summary; the main purpose of this Chapter is to develop a multi-echelon, multi-product, multi-period generic MTP model for the CLSC of a conceptual product considering remanufacturing as a recovery option via fuzzy mixed integer programming. In addition, an important sub-purpose is to put into play the uncertainty related to the quantity and quality of returned products by using fuzzy theory.

## 6.2 Chapter Outline

The rest of this Chapter is organized as follows. In section 6.3, literature review on strategic/tactical planning problem in CLSCs is given. In section 6.4, problem description with network representation of the MTP problem, assumptions, notations and mathematical model formulation are presented. In section 6.5, fuzzy medium-term planning (FMTP) problem is discussed and also this section involves the construction of the membership functions for the fuzzy goal and constraints which have fuzzy minimum, fuzzy maximum and fuzzy equal characteristics, also the transformations of fuzzy model into the crisp equivalent mathematical programs are presented in the same section. In section 6.6, the proposed model is illustrated through a basic example for depicting the validity and practicality. Solutions of the transformed models are achieved by using ILOG OPL Studio version 6.3 including CPLEX 12.1.0 product on an Intel Core i7 2 GHz PC. In section 6.7, proposed FMTP problem is resolved with different target values of acceptance rate (%), unit remanufacturing cost ($), transportation upper bound (units) on remanufactured products and total weekly available time for remanufacturing (hours) in order to investigate the sensitivity of the model and analyze the sensitivity of decision parameters regarding collection-remanufacturing system to variation of satisfaction degrees and objective value. Finally, section 6.8 presents the main conclusions and possible future studies.

## 6.3 Literature Review on Planning Models in Closed-Loop Supply Chains

Pochampally, Nukala, and Gupta (2009) presented the related literature for three main planning levels in RL & CLSCs. According to their study, there are a few quantitative models and case studies take place in the literature since the tactical planning is a relatively new area. They also emphasized that tactical planning dealt with strategic planning in most of the papers.

Ahumada and Villalobos (2009) developed an integrated tactical planning model for production and distribution of perishable agricultural products considering some factors such as price dynamics, product decay, transportation and inventory costs that are generally disregarded in conventional planning models.

Zuluaga and Lourenco (2002) developed a mixed integer linear programming model for a multi-plant production planning model considering product returns. They also incorporate the assemblies and remanufacturable materials to the production processes. The production processes which are taken into account in their study are differentiated from the each other according to the used new materials, returned materials and returned subassemblies. To overcome the uncertainty of the variables, they combined two different optimization and simulation process in the solution phase.

Kreipl and Pinedo (2004) developed a mixed integer programming model for multi-stage medium term planning process of traditional forward supply chains whose outputs are used as inputs in the short-term scheduling process. This general model is also designed to allocate the production of the different products to the various manufacturers in each time period, while taking into account inventory holding costs, production costs, transportation costs and tardiness costs.

Kim et al. (2006) proposed a mixed integer linear programming model in order to maximize total remanufacturing cost savings for supply planning in only RL environment. They focused on optimizing the planning of reverse supply chain considering a remanufacturing system.

Since the requirement of efficient production planning and inventory control mechanisms for the CLSCs, Jayaraman (2006) proposed a linear programming model considering tactical decisions for remanufacturing aggregate production planning (RAPP) with the objective of minimizing total costs that consist of inventory, disassembly, remanufacturing, purchasing and disposal. The proposed model is validated by the data obtained from a mobile phone remanufacturing company.

A multi-product, multi-period mixed integer linear programming model which aims to optimize the design and scheduling of the recovery alternatives such as disassembly, remanufacturing and recycling for the medium-range tactical problem is developed and a novel two phased algorithm is presented for a remanufacturing driven reverse supply chain by Xanthopoulos and Lakovou (2009).

A comprehensive mixed integer linear programming model which involves both strategic and tactical decisions is developed by Salema, Povoa, and Novais (2009) by introducing two-time scaling, namely macro time and micro time. Due to usage of interconnected time scales, integration of travel time between the network levels and usage time for product returns can be considered in their model.

Salema, Povoa, and Novais (2010) extended their previous work based on a graph approach in order to model the CLSC network design while simultaneously determining the tactical decisions such as purchases, production, storage and distribution. In that study, they still considered the travel times, customers' usage time, facilities' processing times, products' bill-of-material and disassembly structures with the help of a novel time modeling approach.

Zhang and Liu (2010) formulated a mixed integer programming model for capacitated production planning problem with remanufacturing option. In their study, demand must be satisfied by capacitated production, remanufacturing and inventory from previous periods. Production and remanufacturing set-up costs are considered all time varying and start-up costs are also included in the first period of the manufacture/remanufacture operations. They also compared their genetic algorithm based approach with the standard branch and bound method.

Shi, Zhang, and Sha (2011) developed a non-linear programming model for the production planning problem of a multi-product CLSC where the demand and returns are uncertain and price-sensitive for all the products. They also considered two channels for meeting the customers' demands: manufacturing of brand new products and remanufacturing option. They developed a Lagrangian relaxation based approach to solve the problem and determined the decisions related to the production amounts of brand-new products, remanufacturing quantities and acquisition price of the used scrap products.

Corominas, Lusa, and Olivella (2012) developed a non-linear mathematical program for joint aggregate planning of manufacturing and remanufacturing of a discrete production system. The non-linearity of the proposed model takes root from the relationship between the rate of recovered products and the price offered for the used products. They considered the price to be paid for used products as a decision variable and at the solution phase, their model is linearised by using piecewise functions.

Subulan, Tasan, and Baykasoglu (2011) developed a multi-echelon, multi-product and multi-period tactical planning model for the CLSC of a conceptual product via fuzzy mixed integer programming. In their model, minimization of the total CLSC costs is addressed as the objective function. They considered the aspiration level of objective value, retailers' and wholesalers' demands, weekly available times for production and remanufacturing, transportation bounds, capacities, product returns and conformity rate as fuzzy data.

## 6.4 Problem Description and Model Development

It is assumed that "new products that are produced in different manufacturing plants or remanufactured products in remanufacturing facilities are transported to the wholesalers which undertake the distribution of these products to the retailers and then end users" in the forward supply chain part of this study. Therefore, customers' demand can be satisfied by two alternative ways: (1) production directly in the different manufacturing plants and (2) remanufacturing option is available for end of life products according to the state of the conceptual used product.

In the reverse supply chain; as with other product recovery network models, used products are collected from the retailers by collection centers or returned product at the retailers are sent directly to the wholesalers which act like hybrid facilities at their end of life while the end user replace it by a new one. When a used product is collected by a collection center or wholesaler, it is sent to a permitted remanufacturing facility. At this remanufacturing facility, returned products are inspected for quality specifications and sorted for remanufacturing process. Finally, the remanufactured products are transported to the wholesalers from the remanufacturing facility to meet the customers' demand by wholesalers or retailers. The recovery system as discussed above can be conceptualized as it is shown in Figure 6.1.

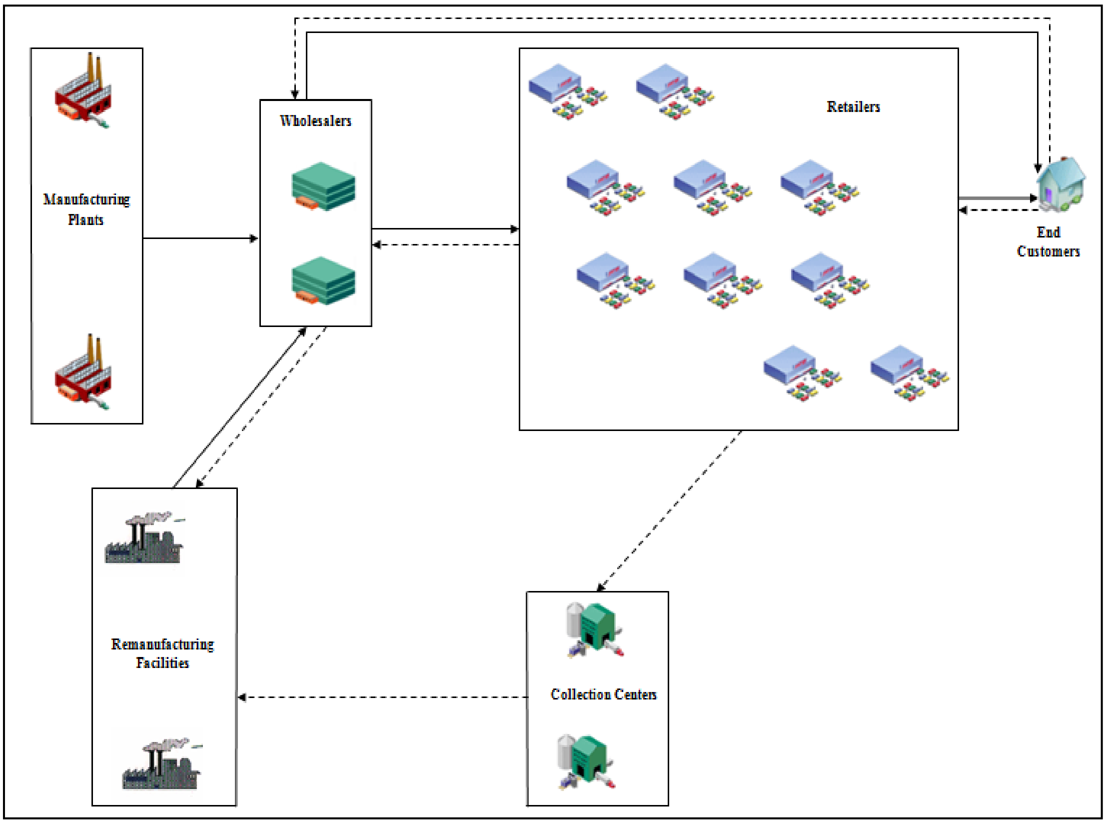



Figure 6.1 A Closed-loop supply chain representation of the conceptual product's remanufacturing system

The first and the most upstream stage (Stage 1) have manufacturing plants in parallel. They both feed stage 2 and 3, which consist of wholesalers and retailers. From the stage 2, new products and remanufactured products can be delivered to directly end customers or to the retailers and the returned products are sent again from the retailers to the stage 2 (Wholesalers) or stage 4 (Collection centers) where the collected used products are inspected, sorted and consolidated. After these processes, the used products that are in appropriate condition for remanufacturing process are transported to the permitted remanufacturing facilities which locate in stage 5.

### *6.4.1 Problem Assumptions*

- Shortages are allowable for both wholesalers' demands and retailers'. Tardiness costs or penalty costs for non-delivering at the end of the planning horizon are incurred in case of any shortage. At the beginning of the planning period, there are no tardy products for the demands of both wholesalers and retailers.
- Cost parameters at all stages of the CLSC network do not change throughout the planning period.
- The retailers do not want to receive any early deliveries.
- It is assumed that there are no quality differences between newly produced products and remanufactured products.
- All transportation times between the stages are assumed to be identical and equal to 1 week. For instance, if a certain amount of newly produced products are shipped in week $t$ from the manufacturing plant $i$ to the wholesaler $j$, then they leave the manufacturing plant $i$ in week $t$ and arrive at the destination in week $t+1$.
- The used products that are not in appropriate condition for remanufacturing process will be disposed after the inspection and sorting process.
- Manufacturing plants can hold finished goods inventory. Also, wholesalers can hold the inventory of both newly produced and remanufactured products. Moreover, used product inventory is held in the collection centers, wholesalers and remanufacturing facilities. In addition, stock of remanufactured products is carried at the remanufacturing facilities.
- All of the beginning inventory levels are assumed to be zero.
- Return rates are different for the collection of used products through wholesalers' level and retailers' level. It is assumed that more product returns are performed through wholesalers.

- Transportation costs between wholesalers-customers and retailers-customers are neglected.
- The amounts of collected used product from a retailer in week *t* should be greater than an uncertain fraction of the demand that is met by the wholesalers in week *t*-1. Similarly, returned product quantity to a wholesaler in week *t* should exceed the uncertain fraction of the demand that is met by the manufacturing plants and remanufacturing facilities in week *t*-1.
- Sufficient amounts of used products are available for collection.

### *6.4.2 Indices and Sets*

$p$ refers to the conceptual product type; $p \in P$

$i$ refers to the manufacturing plants; $i \in I$

$j$ refers to the wholesalers; $j \in J$

$k$ refers to the retailers; $k \in K$

$l$ refers to the collection centers; $l \in L$

$r$ refers to the remanufacturing facilities; $r \in R$

$t$ refers to time period, week $t \in T$

### *6.4.3 Model Parameters*

$DW_{pjt}$ weekly demand for product type $p$ at the wholesaler $j$ by the end of week $t$

$DR_{pkt}$ weekly demand for product type $p$ at the retailer $k$ by the end of week $t$

$AP$ available time for production of all manufacturing plants

$AR$ available time for remanufacturing of all remanufacturing facilities

$S1_p$ returned rate of $p$-type used product that is returned to retailers and collected by collection centers or wholesalers at the end of any given week

$S2_p$ returned rate of $p$-type used product that is returned to wholesalers and shipped to directly remanufacturing facilities without any collection centers at the end of any given week

$CR_p$ rate of returned product type $p$ that is in appropriate condition for remanufacturing processes (Conformity rate or acceptance ratio)

$PC_{pi}$ production cost per unit of product type $p$ in manufacturing plant $i$

$Pt_{pi}$ required time (in hours) to produce one unit of product type $p$ in manufacturing plant $i$. The $Pt_{pi}$ is just an estimate of the average time required to produce one unit since it combines processing times with set-up times

$Rt_{pr}$ required time (in hours) to remanufacture one unit of returned product type $p$ in remanufacturing facility $r$

$CC_p$ collection cost per unit of used product type $p$

$DC_{pr}$ disposal cost per unit of used product type $p$ at the remanufacturing facility $r$

$RC_{pr}$ remanufacturing cost for per unit of $p$-type returned product at the remanufacturing facility $r$

$TC_p$ transportation cost for one unit of newly manufactured or remanufactured product type $p$ per kilometer

$TC1_p$ transportation cost for one unit of collected used product type $p$ per kilometer

$H1_p$ weekly holding or storage cost in any manufacturing plant for one unit of finished product type $p$

$H2_p$ weekly holding or storage cost in any wholesaler for one unit of newly produced or remanufactured product type $p$

$H3_p$ weekly holding or storage cost in any wholesaler for one unit of returned product type $p$

$H4_p$ weekly holding or storage cost in any collection center for one unit of returned product type $p$

$H5_p$ weekly holding or storage cost in any remanufacturing facility for one unit of used product type $p$

$H6_p$ weekly holding or storage cost in any remanufacturing facility for one unit of remanufactured product type $p$

$RCap_{pr}$ maximum storage capacity of remanufacturing facility $r$ for both used and remanufactured product type $p$

$CCap_{pl}$ maximum storage capacity of collection center $l$ for used product type $p$

$PE_p$ the tardiness cost per unit of product per week for an order of product type $p$ that arrive late at each wholesaler

$PJ_p$ the tardiness cost per unit of product per week for an order of product type $p$ that arrive late at each retailer

$ND_p$ the penalty cost for never delivering one unit of *p*-type product to each retailer and to the each wholesaler at the end of the planning horizon

$UB_{pi}$ upper bounds on quantities of product type *p* to be shipped from the manufacturing plant *i* to the wholesalers for each time period

$UB1_{pr}$ upper bounds on quantities of remanufactured product type *p* to be shipped from the remanufacturing facility *r* to the wholesalers for each time period

$d1_{ij}$ the distance between manufacturing plant *i* and the wholesaler *j*

$d2_{jk}$ the distance between wholesaler *j* and the retailer *k*

$d3_{kl}$ the distance between retailer *k* and the collection center *l*

$d4_{lr}$ the distance between collection center *l* and the remanufacturing facility *r*

$d5_{rj}$ the distance between remanufacturing facility *r* and the wholesaler *j*

### *6.4.4 Decision Variables*

In order to formulate the problem as a mixed integer program, the following decision variables are defined;

$X_{pit}$ number of units of product type *p* that are produced at manufacturing plant *i* during week *t*

$R_{prt}$ number of units of product type *p* that are remanufactured at remanufacturing facility *r* during week *t*

$Y1_{pijt}$ number of units of product type *p* shipped to the wholesaler *j* from the manufacturing plant *i* in week *t*

$Z_{pjkt}$ quantity of product type *p* shipped to the retailer *k* from the wholesaler *j* in week *t*

$Y2_{pklt}$ quantity of returned product type *p* collected from the retailer *k* and transported to the collection center *l* in week *t*

$Y3_{pkjt}$ quantity of returned product type *p* transported from the retailer *k* to the wholesaler *j* in week *t*

$Y4_{pjrt}$ quantity of returned product type *p* shipped to the remanufacturing facility *r* from the wholesaler *j* in week *t*

$RET_{pjt}$ total amounts of used product type *p* returned to the wholesaler *j* in week *t*

$W1_{plrt}$ quantity of returned product type *p* shipped to the remanufacturing facility *r* from the collection center *l* in week *t*

$W2_{prjt}$ quantity of remanufactured product type *p* shipped to the wholesaler *j* from the remanufacturing facility *r* in week *t*

$IM_{pit}$ quantity of finished product type *p* in storage at the manufacturing plant *i* at the end of week *t*

$IW_{pjt}$ quantity of newly produced or remanufactured product type *p* in storage at the wholesaler *j* at the end of week *t*

$IW1_{pjt}$ quantity of returned product type *p* in storage at the wholesaler *j* at the end of week *t*

$IC_{plt}$ quantity of returned product type *p* in storage at the collection center *l* at the end of week *t*

$IR1_{prt}$ quantity of used product type *p* in storage at the remanufacturing facility *r* at the end of week *t*

$IR2_{prt}$ quantity of remanufactured product type *p* in storage at the remanufacturing facility *r* at the end of week *t*

$T1_{pjt}$ quantity of product type *p* that is tardy (have not yet arrived) at the wholesaler *j* in week *t*

$T2_{pkt}$ quantity of product type *p* that is tardy at the retailer *k* by the end of week *t*

$Q_1$, $Q_2$, $Q_3$, $Q_4$, $Q_5$, $Q_6$ $Q_7$ $Q_8$ *and* $Q_9$ binary variables for transformation of non-linear constraints into the linear form

### *6.4.5 Mathematical Formulation of the Fuzzy Medium-Term Planning (FMTP) Problem*

By using the indices and parameters as defined above, the objective function of the multi-echelon, multi-product and multi-period MTP model which considers recovery option such as remanufacturing is given by the following equations:

Minimize the total costs of CLSC that which consist of;

1. Total production costs;

$$\sum_{p=1}^{P}\sum_{i=1}^{I}\sum_{t=1}^{T} X_{pit}\,.\,PC_{pi} \tag{6.1}$$

2. Total transportation costs between the several stages;

$$\sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{p=1}^{P}\sum_{t=1}^{T} d1_{ij}\,.\,Y1_{pijt}\,.\,TC_{P} + \sum_{p=1}^{P}\sum_{j=1}^{J}\sum_{k=1}^{K}\sum_{t=1}^{T} d2_{jk}\,.\,Z_{pjkt}\,.\,TC_{p} +$$
$$\sum_{p=1}^{P}\sum_{k=1}^{K}\sum_{r=1}^{R}\sum_{t=1}^{T} d3_{kl}.\,Y2_{pklt}\,.\,TC1_{p} + \sum_{p}^{P}\sum_{l}^{L}\sum_{r}^{R}\sum_{t}^{T} d4_{lr}\,.\,W1_{plrt}.\,TC1_{p} +$$
$$\sum_{p=1}^{P}\sum_{r=1}^{R}\sum_{j=1}^{J}\sum_{t=1}^{T} d5_{rj}\,.\,W2_{prjt}.\,TC_{p} + \sum_{p}^{P}\sum_{k}^{K}\sum_{j}^{J}\sum_{t}^{T} d2_{jk}.\,Y3_{pkjt}\,.\,TC1_{p} +$$
$$\sum_{p}^{P}\sum_{j}^{J}\sum_{r}^{R}\sum_{t}^{T} d5_{rj}.\,Y4_{pjrt}\,.\,TC1_{p} \tag{6.2}$$

3. Total remanufacturing costs;

$$\sum_{p}^{P}\sum_{r}^{R}\sum_{t}^{T} R_{prt}\,.\,RC_{pr} \tag{6.3}$$

4. Total disposal costs for the non-remanufactured products;

$$\sum_{p}^{P}\sum_{l}^{L}\sum_{r}^{R}\sum_{t}^{T} W1_{plrt}\,.\,(1-CR_{p}).\,DC_{pr} + \sum_{p}^{P}\sum_{j}^{J}\sum_{r}^{R}\sum_{t}^{T} Y4_{pjrt}\,.\,(1-CR_{p}).\,DC_{pr} \tag{6.4}$$

5. Total inventory holding costs at the manufacturing plants, wholesalers, collection centers and remanufacturing facilities, respectively;

$$\sum_{p}^{P}\sum_{i}^{I}\sum_{t}^{T} IM_{pit} \, . H1_p + \sum_{p}^{P}\sum_{j}^{J}\sum_{t}^{T} IW_{pjt} \, . H2_P + \sum_{p}^{P}\sum_{j}^{J}\sum_{t}^{T} IW1_{pjt} \, . H3_p + \sum_{p}^{P}\sum_{l}^{L}\sum_{t}^{T} IC_{plt} \, . H4_p + \sum_{p}^{P}\sum_{r}^{R}\sum_{t}^{T} IR1_{prt} \, . H5_p + \sum_{p}^{P}\sum_{r}^{R}\sum_{t}^{T} IR2_{prt} \, . H6_p \quad (6.5)$$

6. Total collection costs for the used products;

$$\sum_{p}^{P}\sum_{j}^{J}\sum_{t}^{T} RET_{pjt} \, . CC_p + \sum_{p}^{P}\sum_{k}^{K}\sum_{l}^{L}\sum_{t}^{T} Y2_{pklt} \, . CC_p \quad (6.6)$$

7. Total tardiness costs for the wholesalers and retailers;

$$\sum_{p}^{P}\sum_{j}^{J}\sum_{t}^{T-1} T1_{pjt} \, . PE_p + \sum_{p=1}^{P}\sum_{k=1}^{K}\sum_{t=1}^{T-1} T2_{pkt} \, . PJ_p \quad (6.7)$$

8. Total penalty costs for non-delivery products over the planning period;

$$\sum_{p}^{P}\sum_{j}^{J} T1_{pjT} \, . ND_p + \sum_{p}^{P}\sum_{k}^{K} T2_{pkT} \, . ND_p \qquad t = T \quad (6.8)$$

Constraints included in the medium-term planning model considering reverse flows are expressed by equations (6.9) to (6.34),

$$\sum_{p}^{P} X_{pit} \, . Pt_{pi} \leq \widetilde{AP} \qquad \forall i, \forall t \quad (6.9)$$

$$\sum_{p}^{P} R_{prt} \, . Rt_{pr} \leq \widetilde{AR} \qquad \forall r, \forall t \quad (6.10)$$

$$IM_{pit} = IM_{pit-1} + X_{pit} - \sum_{j}^{J} Y1_{pijt} \qquad \forall p, \forall i, \forall t \quad (6.11)$$

$$\sum_{j}^{J} Z_{pjkt-1} = \widetilde{DR}_{pkt} + T2_{pkt-1} - T2_{pkt} \qquad \forall p, \forall k, \forall t \tag{6.12}$$

$$\sum_{l}^{L} Y2_{pklt} + \sum_{j}^{J} Y3_{pkjt} \geq \sum_{j}^{J} Z_{pjkt-1} . \widetilde{S1}_{p} \qquad \forall p, \forall k, \forall t \tag{6.13}$$

$$IC_{plt} = IC_{plt-1} + \sum_{k}^{K} Y2_{pklt-1} - \sum_{r}^{R} W1_{plrt} \qquad \forall p, \forall l, \forall t \tag{6.14}$$

$$\sum_{j}^{J} Y1_{pijt} \leq \widetilde{UB}_{pi} \qquad \forall p, \forall i, \forall t \tag{6.15}$$

$$\sum_{j}^{J} W2_{prjt} \leq \widetilde{UB1}_{pr} \qquad \forall p, \forall r, \forall t \tag{6.16}$$

$$RET_{pjt} \geq \left( \sum_{i}^{I} Y1_{pijt-1} + \sum_{r}^{R} W2_{prjt-1} + IW_{pjt-1} - IW_{pjt} - \sum_{k}^{K} Z_{pjkt} \right) . \widetilde{S2}_{p} +$$

$$\sum_{k}^{K} Y3_{pkjt-1} \quad \forall p, \forall j, \forall t \tag{6.17}$$

$$\sum_{r}^{R} Y4_{pjrt} \leq RET_{pjt} \qquad \forall p, \forall j, \forall t \tag{6.18}$$

$$IR1_{prt} = IR1_{prt-1} + \left( \sum_{l}^{L} W1_{plrt-1} + \sum_{j}^{J} Y4_{pjrt-1} \right) . \widetilde{CR}_{P} - R_{prt} \qquad \forall p, \forall r, \forall t \tag{6.19}$$

$$IR2_{prt} = IR2_{prt-1} + R_{prt} - \sum_{j}^{J} W2_{prjt} \qquad \forall p, \forall r, \forall t \tag{6.20}$$

$$IR1_{prt} + IR2_{prt} \leq \widetilde{RCAP}_{pr} \qquad \forall p, \forall r, \forall t \tag{6.21}$$

$$IC_{plt} \leq \widetilde{CCAP}_{pl} \qquad \forall p, \forall l, \forall t \tag{6.22}$$

$$\sum_{k}^{K} Z_{pjk1} \leq \max\left(0, IW_{pj0}\right) \qquad \forall p, \forall j \tag{6.23}$$

$$\sum_{k}^{K} Z_{pjkt} \leq IW_{pjt-1} + \sum_{i}^{I} Y1_{pijt-1} + \sum_{r}^{R} W2_{prjt-1} \quad \forall p, \forall j, \forall t > 1 \tag{6.24}$$

$$IW_{pj1} = \max\left( 0, IW_{pj0} - \widetilde{DW}_{pj1} - \sum_{k}^{K} Z_{pjk1} \right) \qquad \forall p, \forall j \tag{6.25}$$

$$IW_{pjt} = \max\left( 0, IW_{pjt-1} + \sum_{i}^{I} Y1_{pijt-1} + \sum_{r}^{R} W2_{prjt-1} - \widetilde{DW}_{pjt} - \sum_{k}^{K} Z_{pjkt} - T1_{pjt-1} \right)$$

$$\forall p, \forall j, \forall t > 1 \tag{6.26}$$

$$IW1_{pj1} = \max\left( 0, IW1_{pj0} - \sum_{r}^{R} Y4_{pjr1} \right) \qquad \forall p, \forall j \tag{6.27}$$

$$IW1_{pjt} = \max\left(0, IW1_{pjt-1} + RET_{pjt} - \sum_{r}^{R} Y4_{pjrt}\right) \qquad \forall p, \forall j, \forall t > 1 \qquad (6.28)$$

$$IW_{pjt} + IW1_{pjt} \leq \widetilde{WCAP}_{pj} \qquad \forall p, \forall j, \forall t \qquad (6.29)$$

$$T1_{pj1} = \max(0, \widetilde{DW}_{pj1} + T1_{pj0} - IW_{pj0}) \qquad \forall p, \forall j \qquad (6.30)$$

$$T1_{pjt} = \max\left(0, \widetilde{DW}_{pjt} + T1_{pjt-1} + \sum_{k}^{K} Z_{pjkt} - IW_{pjt-1} - \sum_{i}^{I} Y1_{pijt-1} - \sum_{r}^{R} W2_{prjt-1}\right)$$

$$\forall p, \forall j, \forall t > 1 \qquad (6.31)$$

$$T2_{pk1} = \max\left(0, \widetilde{DR}_{pk1} + T2_{pk0}\right) \qquad \forall p, \forall k \qquad (6.32)$$

$$T2_{pkt} = \max\left(0, \widetilde{DR}_{pkt} + T2_{pkt-1} - \sum_{j}^{J} Z_{pjkt-1}\right) \forall p, \forall k, \forall t > 1 \qquad (6.33)$$

$$X_{pit}, R_{prt}, Y1_{pijt}, Z_{pjkt}, Y2_{pklt}, W1_{plrt}, W2_{prjt}, Y3_{pkjt}, Y4_{pjrt} \geq 0 \quad \textit{and integers}.$$
$$\textit{All other variables are continuous and } Q_1, Q_2, Q_3, Q_4, Q_5, Q_6, Q_7, Q_8, Q_9 \in (0,1) \qquad (6.34)$$

Constraints (6.9) and (6.10) limit the total production and remanufacturing quantities in the manufacturing plants and remanufacturing facilities, respectively. In other words, each manufacturing plant and remanufacturing facility can operate only in the regular operating time of that period (126 hours). But, in real life situations the weekly production and remanufacturing capacity may be expressed in 24x 7=168 hours at maximum theoretically with the additional overtime under assumption of no breakdowns. Therefore, total weekly available time for production and remanufacturing can be considered as fuzzy data. According to constraint (6.11), one can calculate the inventory level of the finished product type *p* at each manufacturing plant *i* in each time period. Constraint (6.12) maintains that all amounts of demand related to a retailer for each type of product in each time period may not be satisfied. In other words, there is a possibility of tardy products (backordering state). Also, this constraint forces to satisfy the remaining tardy products from the previous period. However, the shipment quantities from the wholesalers to the retailers are limited with this constraint. Constraint (6.13) is the conservation of flow constraint for balancing the quantities of returned products. According to the governmental regulations, total amounts of returned/collected products to a retailer in week *t* should be greater than multiplication of satisfied demand of this retailer in week *t* by an uncertain return rate. Constraint (6.14) displays the inventory level of the used product type *p* at each collection center in each time period. Constraints (6.15) and

(6.16) refer to the transportation capacity constraints. In fact, there are upper bounds on the transportation quantities from the any given manufacturing plant and remanufacturing facility to all wholesalers. Constraint (6.17) is again conservation of flow constraint for balancing the quantities of returned products to each wholesaler. According to this constraint, total amounts of returned/collected products to a wholesaler in week *t* should be greater than multiplication of satisfied demand of this wholesaler in week *t* by another uncertain return rate plus collected used products from all retailers. Constraint (6.18) makes sure that total quantities of shipped used products from any given wholesaler to the remanufacturing facilities in week *t* cannot get over the returned product quantity to this wholesaler in week *t*. According to constraints (6.19) and (6.20), one can calculate the inventory levels of both used and remanufactured product type *p* at each remanufacturing facility in each time period. In constraint (6.19), uncertainty related to the acceptance of returned products to the remanufacturing operation is taken into account. Constraints (6.21) and (6.22) ensure that total inventory amounts at each remanufacturing facility and at each collection center can't exceed the storage capacity of that remanufacturing facility and collection center, respectively. Constraint (6.23) ensures that the amount of *p*-type product shipped to the retailers from the wholesalers in week 1 can't exceed the initial storage level at the beginning of the planning horizon. Constraint (6.23) can be extended for the other planning periods as in the equation (6.24). Thus, in week *t*, the total volume of shipped products to the retailers from the each wholesaler can't exceed the previous period inventory level and the amount of both newly produced and remanufactured products in week *t-1*. Inventory holding levels of newly produced or remanufactured products at each wholesaler can be calculated according to equations (6.25) and (6.26) for each time period. Thus, in week 1 demand of that week and the outgoing flows from the wholesaler must be subtracted from the initial storage level at the beginning of planning horizon. Similar to the equation (6.25), in equation (6.26) incoming flows to the wholesaler must be added to the previous period inventory level and outgoing flows must be subtracted while calculating the storage level in week *t*. Similarly, constraints (6.27) and (6.28) show the inventory levels of returned products to the wholesalers. Constraint (6.29) shows storage capacity of the wholesalers for both newly produced/remanufactured and returned products. In equations (6.30) and (6.31), constraints regarding number of products that are tardy in each time period and number of products not delivered for each wholesaler at the end of the planning horizon are examined. Similar to the constraints (6.30) and (6.31), in equation (6.32) and (6.33), constraints regarding number of products tardy in each time period and number of products not delivered for each retailer at the end of the planning horizon are examined. Constraint (6.34) preserves the non-negativity of decision variables.

Generally, most variables in the MIP formulations are continuous variables. Since the production/remanufacturing and distribution variables are subject to disjunctive constraints, these variables should take integer values. Moreover, note that those constraints in which a variable is equal to the "max of an expression or 0" are convex and non-linear (Kreipl and Pinedo, 2004; Pinedo, 2005). Since the negative values taken by these related decision variables are not desired, these non-linear constraints are required for control.

In order to ensure that the given variable remains non-negative, an additional binary variable has to be introduced. For expressing non-linear implications by linear constraints, we must introduce an additional binary variable for each non-linear constraint in the solution phase. For instance, to express the following non-linear constraint (6.26) into a linear form;

$$IW_{pjt} = \max\left(\begin{array}{c} 0, IW_{pjt-1} + \sum_{i}^{I} Y1_{pijt-1} + \sum_{r}^{R} W2_{prjt-1} - \widetilde{DW}_{pjt} \\ - \sum_{k}^{K} Z_{pjkt} - T1_{pjt-1} \end{array}\right) \quad \forall p, \forall j, \forall t > 1$$

Firstly, we must introduce a new binary variable $Q_1$ for the elimination of the max operator;

$$Q1 = \left\{\begin{array}{ll} 1, if\ IW_{pjt-1} + \sum_{i}^{I} Y1_{pijt-1} + \sum_{r}^{R} W2_{prjt-1} - \widetilde{DW}_{pjt} - \sum_{k}^{K} Z_{pjkt} - T1_{pjt-1} \geq 0 \\ 0, \quad Otherwise \end{array}\right\} \quad (6.35)$$

The linear form of the non-linear expression consists of three inequalities;

$$IW_{pjt} - IW_{pjt-1} - \sum_{i}^{I} Y1_{pijt-1} - \sum_{r}^{R} W2_{prjt-1} + \widetilde{DW}_{pjt} + \sum_{k}^{K} Z_{pjkt} + T1_{pjt-1} \leq M.(1 - Q_1)$$

$$IW_{pjt} \leq M.Q_1$$

$$IW_{pjt} \geq IW_{pjt-1} + \sum_{i}^{I} Y1_{pijt-1} + \sum_{r}^{R} W2_{prjt-1} - \widetilde{DW}_{pjt} - \sum_{k}^{K} Z_{pjkt} - T1_{pjt-1} \quad (6.36)$$

Where, $M$ is a big number. When $Q_1$=1, we assume that the state variable $IWpjt$ is positive. In the opposite case, when $Q_1$=0, we assume that the state variable $IWpjt$ is equal to zero. All other non-linear expressions are transformed into the linear form in a similar way.

## 6.5 Employing Different Fuzzy Approaches to the Proposed FMTP Problem

Since the deterministic models assume certainty in all aspects of the problem although some of the parameters cannot be precisely set like capacities and target for objective function achievement (Baykasoglu & Gocken, 2006, 2007, 2012; Bilgen, 2010a), a fuzzy mixed integer program is formulated in this Chapter. In other words, some of the parameters utilized in the proposed model such as capacities, demands, return rates, acceptance rates, weekly available production/remanufacturing times, transportation upper bounds and target for the objective function achievement are imprecisely set.

The constraints including the total available time for production/remanufacturing, (6.9) and (6.10), demand satisfaction constraint (6.12) and the associated constraints which involve the demands of wholesalers and retailers such as inventory and tardiness equations (6.25), (6.26), (6.30), (6.31), (6.32) and (6.33), upper bounds on the transportation quantities (6.15) and (6.16), storage capacities of both collection centers, remanufacturing facilities and wholesalers (6.21), (6.22) and (6.29), conservation of flow constraints for the returned products including the return rates (6.13) and (6.17), inventory equation that used acceptance ratio (6.19) and finally objective function achievement level are modeled by using fuzzy sets with linear membership functions. The constraints (6.9), (6.10), (6.15), (6.16), (6.21), (6.22) and (6.29) are presented by a fuzzy set whose membership function $\mu_i(x)$ is defined as follows (Zimmermann, 1976);

$$\mu_i(x) = \begin{cases} 1, & if\ (AX)_i \le b_i \\ 1 - ((AX)_i - b_i)/d_i & if\ b_i < (AX)_i \le b_i + d_i \\ 0, & if\ (AX)_i > b_i + d_i \end{cases} \qquad (6.37)$$

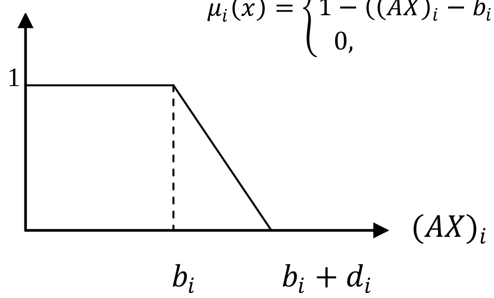



Figure 6.2 The membership function and analytical definition of fuzzy minimum

Where $(Ax)_i$ represents the left hand side of the fuzzy constraints, $b_i$ represents the right hand side of the fuzzy constraints and $d_i$ is the tolerance level which a decision maker can tolerate in the accomplishment of the $i^{th}$ constraint of the fuzzy inequality (Baykasoglu and Gocken, 2008). Membership function of constraints (6.13), (6.17) and (6.19) are defined by $\mu_i'(x)$ as shown in Figure 6.3 and equation (6.38):

$$\mu_{Z_k}(Z) = \begin{cases} 1, & if\ (AX)_i \ge b_i \\ \dfrac{(AX)_i - (b_i - d_i)}{d_i}, & if\ \ b_i - d_i \le (AX)_i \le b_i \\ 0, & if\ \ (AX)_i \le b_i - d_i \end{cases} \qquad (6.38)$$

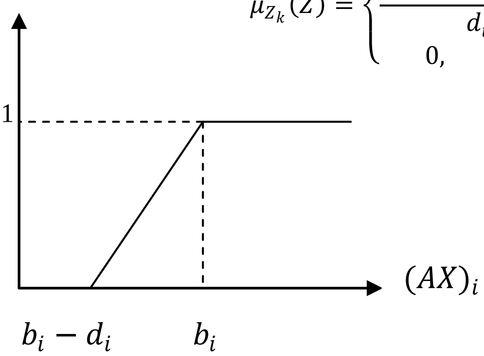
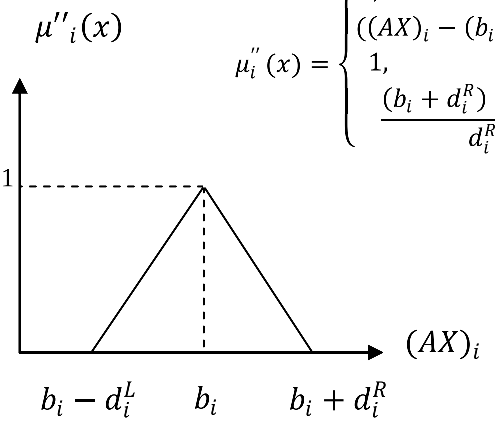



Figure 6.3 Membership function and analytical definition of fuzzy maximum

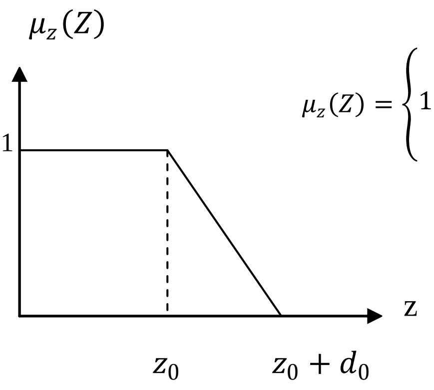
Similarly, linear membership function of the demand satisfaction constraint (6.12) and the associated constraints (6.25), (6.26), (6.30), (6.31), (6.32) and (6.33) are defined by $\mu_i''(x)$ as shown in Figure 6.4 and equation (6.39):




$$\mu_i''(x) = \begin{cases} 0, & if\ (AX)_i \le b_i - d_i^L \\ ((AX)_i - (b_i - d_i^L))/d_i^L & if\ b_i - d_i^L \le (AX)_i \le b_i \\ 1, & if\ (AX)_i = b_i \\ \dfrac{(b_i + d_i^R) - (AX)_i}{d_i^R} & if\ (AX)_i \ge b_i + d_i^R \end{cases} \quad (6.39)$$

Figure 6.4 Membership function and analytical definition of fuzzy equal

The membership function of the fuzzy goal is constructed as shown in Figure 6.5 and equation (6.40), where $d_0$ is an aspiration level of the objective function value that is set by the decision maker:




$$\mu_z(Z) = \begin{cases} 1, & if\ z < z_0 \\ 1 + \dfrac{z_0 - z}{d_0}, & if\ z_0 \le z \le z_0 + d_0 \\ 0, & if\ z_0 + d_0 < z \end{cases} \quad (6.40)$$

Figure 6.5 Membership function and analytical definition of the fuzzy goal

Baykasoglu and Gocken (2008) classified these models with fuzzy objectives and fuzzy right hand values of the constraints as type-5 fuzzy mathematical programming models and stated as follows;

$$max/\min \tilde{f}\,(x_j, c_j)$$
$$s.t.\;\; g(x_j, a_j)\{\le,\ge,=\}\tilde{b}_i \qquad i=1,2,\ldots.m \qquad j=1,2,\ldots\ldots.n \qquad (6.41)$$

For the solution of this type of fuzzy mathematical programming models, several authors used different fuzzy aggregation operators to transform the fuzzy mathematical program into the crisp equivalent. In this Chapter, four different solution approaches namely the "max-min operator" (Zimmermann, 1978), the ‘‘convex combination of min-operator and max-operator" (Zimmermann, 1996), the ‘‘fuzzy-and operator" (Werner, 1987), and "Li's two-phase approach" (Li, 1990) are employed in order to provide a more confident solution for the decision maker.

### *6.5.1 Zimmermann's Approach Max-Min Operator*

Zimmermann (1978) first proposed max-min operator to solve fuzzy mathematical programming models or type-5 fuzzy models. According to this approach, relationship between the constraints and objective function(s) is fully symmetric and there is no difference between the constraints and objective(s). The fuzzy decision is the selection of the activities which simultaneously satisfy objective function(s) and constraints. The fuzzy decision is the intersection of fuzzy constraints' and fuzzy objective(s)' membership functions (Baykasoglu & Gocken, 2008, 2011). The crisp mathematical programming model is obtained by transforming max-min problem by using the auxiliary variable $\lambda$ which is defined as follows:

$$\max \quad \lambda$$
$$S.t. \quad \mu_k(x_j, c_j) \ge \lambda \qquad \forall k \in K$$
$$\lambda \in [0,1]$$
$$g(x_j, a_{ij})\{\le,\ge,=\}b_i \qquad \forall i \in I \; and \; j \in J \qquad (6.42)$$

Where $c_j$ are the coefficients of objective function, $x_j$ are the decision variables, $a_{ij}$ are technological coefficients of constraints, $b_i$ are right hand side values of constraints and $\lambda$ is the overall satisfactory level of compromise. By using the formulation (6.42) of above inequalities, the final equivalent crisp mixed integer programming formulation of the stated problem can be formally defined with the addition of the equations (6.11), (6.14), (6.18), (6.20), (6.23), (6.24), (6.27), (6.28) and all of the transformed constraints. In other words, the non-fuzzy constraints are added to the fuzzy mathematical model and the remaining unalterable. Due to the large amount of fuzzy constraints, they are divided into three classes and only the some of them are converted into crisp equivalent by using max-min method as shown in Table 6.1.

Table 6.1 Summary of the transformation process for the stated problem by using max-min method

**Objective:** $Max\ \ \lambda$

$Total\ cost\ of\ the\ CLSC\ \leq\ z_0 + d_0.(1-\lambda)$

**Constraint type-1:** Fuzzy linear constraints whose right hand value consists of only one parameter (6.9), (6.10), (6.12), (6.15), (6.16), (6.21), (6.22) and (6.29). For instance, constraint (6.9):

$$\sum_{p=1}^{P} X_{pit}.Pt_{pi} \leq AP + d_1.(1-\lambda) \qquad \forall i, \forall t$$

**Constraint type-2:** Fuzzy linear constraints whose right hand value is equal to multiplication of a fuzzy parameter by a variable or summation of variables (6.13), (6.17) and (6.19). For instance, constraint (6.13):

$$\sum_{l}^{L} Y2_{pklt} + \sum_{j}^{J} Y3_{pkjt} \geq \sum_{j}^{J} Z_{pjkt-1}.S1_p - d_4.\left(\sum_{j}^{J} Z_{pjkt-1} - \lambda\right) \qquad \forall p, \forall k, \forall t$$

**Constraint type-3:** Fuzzy non-linear constraints whose right hand value involves only one fuzzy parameter (6.25), (6.26), (6.30), (6.31), (6.32) and (6.33). For instance, constraint (6.25):

$$IW_{pj1} - SV1_{pj1} \leq M.(1 - Q1_{pj1}) \qquad \forall p, \forall j$$

$$IW_{pj1} \leq M.Q1_{pj1} \qquad \forall p, \forall j$$

$$IW_{pj1} \geq SV1_{pj1} \qquad \forall p, \forall j$$

$$SV1_{pj1} \leq IW_{pj0} - DW_{pj1} + d_{12}.(1-\lambda) - \sum_{k}^{K} Z_{pjk1}$$

$$SV1_{pj1} \geq IW_{pj0} - DW_{pj1} - d_{12}.(1+\lambda) - \sum_{k}^{K} Z_{pjk1}$$

For the transformation of the fuzzy non-linear constraints including fuzzy demand data into the linear crisp equivalent, additional state variables (SV) which are equal to the right hand side value of the max expression should be added with the additional binary variables as shown in the above inequalities in Table 6.1.

Therefore, five additional constraints are required for the transformation of each fuzzy non-linear constraint into the crisp linear form. After the solution of the stated model, if λ is equal to 1, then it can be said that all of the constraints are fully satisfied otherwise they are partly satisfied.

### *6.5.2 Convex Combination of the Min-Operator and Max-Operator*

For some applications, it may be important for the aggregator used to map above the "max operator" and below the "min operator". The γ -operator can provide such a connection. An acceptable compromise between empirical fit and computational efficiency seems to be the convex combination of the min operator and the max operator (Kaynak, Zadeh, Türkşen, and Rudas, 1998). By using the convex combination of the min operator and max operator, the fuzzy sets are aggregated and the fuzzy sets decision may be defined as follows (Miller, Leung, Azhar, and Sargent, 1997);

$$\mu_D(x) = \gamma . min_{k=1}^{K} \mu_k(x) + (1-\gamma) . max_{k=1}^{K} \mu_k(x) \tag{6.43}$$

Where $\mu_k(x)$ is the membership functions of the fuzzy sets which are aggregated using the convex combination of the min-operator and the max operator, $\gamma$ is the degree of compensation which has the effective value of 0.6 in most cases (Zimmermann, 1996), and $k$ denotes the $k^{th}$ fuzzy constraint. In this approach, two new auxiliary variables ($\lambda_1$ and $\lambda_2$) are added to the model.

$$\lambda_1 = min_{k=1}^{K} \mu_k(x) \; and \; \lambda_2 = max_{k=1}^{K} \mu_k(x) \tag{6.44}$$

$\lambda_1$ represents the degree of satisfaction of the least satisfied constraint, $\lambda_2$ represents the degree of satisfaction of the most satisfied constraint ($0 \leq \lambda_1 \leq 1$ and $0 \leq \lambda_2 \leq 1$).

The fuzzy maximizing decision can be expressed as below;

$$max \;\; \mu_D(x) = max \;\; (\gamma . \lambda_1 + (1-\gamma) . \lambda_2)$$

$$S.t. \quad \lambda_1 \leq \mu_k(x) \quad and \quad \lambda_2 \leq \mu_k(x) \qquad \forall k$$
$$For\ at\ least\ one\ \ k \in (1, \dots \dots K) \tag{6.45}$$

Solution of the above fuzzy model can be yielded by solving the following traditional linear programming model.

$$max \ \ \gamma.\lambda_1 + (1-\gamma).\lambda_2$$
$$(AX)_i \leq b_i + d_i.(1-\lambda_1)$$
$$(AX)_i \leq b_i + d_i.(1-\lambda_2) + M.\pi_i$$
$$\sum_{i=1}^{k} \pi_i = k - 1$$
$$0 \leq \lambda_1 \leq 1, \quad 0 \leq \lambda_2 \leq 1, \quad X \geq 0 \ \ and \quad \pi_i \in (0,1) \tag{6.46}$$

Where $M$ is a big positive number. The objective function and fuzzy constraints are transformed by two groups of constraints, one for the min operator; the other one for the max operator. The objective function maximizes the linear combination of the least satisfied constraint and the satisfaction level of the most satisfied constraint (Bilgen, 2010a, 2008). By using the formulation (6.46) of the above inequalities, the auxiliary model of the FMTP problem can be explained as follows with the addition of the non-fuzzy constraints. Even so, summary of the transformation process for the stated problem by using convex combination of the min-operator and max-operator is given in Table 6.2.

When we compared this method with the max-min operator approach in terms of total number of constraints in the transformed model, all fuzzy linear constraints are used for one more time in the crisp equivalent. Also, in terms of fuzzy non-linear constraints, two additional constraints are required (Seven constraints in totally) for transformation of each fuzzy non-linear constraint into the crisp linear form.

Table 6.2 Summary of the transformation process for the stated problem by using convex combination of the min-operator and max-operator

**Objective:** $max \quad \gamma.\lambda_1 + (1-\gamma).\lambda_2$

$Total\ cost\ of\ the\ CLSC \ \leq \ z_0 + d_0.(1-\lambda_1)$

$Total\ cost\ of\ the\ CLSC \ \leq \ z_0 + d_0.(1-\lambda_2) + M.\pi_1$

**Constraint type-1:** Fuzzy linear constraints whose right hand value consists of only one parameter (6.9), (6.10), (6.12), (6.15), (6.16), (6.21), (6.22) and (6.29). For instance, constraint (6.9):

$$\sum_{p=1}^{P} X_{pit}.Pt_{pi} \leq AP + d_1.(1-\lambda_1) \qquad \forall i, \forall t$$

$$\sum_{p=1}^{P} X_{pit}.Pt_{pi} \leq AP + d_1.(1-\lambda_2) + M.\pi_2 \qquad \forall i, \forall t$$

**Constraint type-2:** Fuzzy linear constraints whose right hand value is equal to multiplication of a fuzzy parameter by a variable or summation of variables (6.13), (6.17) and (6.19). For instance, constraint (6.13):

$$\sum_{l}^{L} Y2_{pklt} + \sum_{j}^{J} Y3_{pkjt} \geq \sum_{j}^{J} Z_{pjkt-1}.S1_p - d_4.\left(\sum_{j}^{J} Z_{pjkt-1} - \lambda_1\right) \qquad \forall p, \forall k, \forall t$$

$$\sum_{l}^{L} Y2_{pklt} + \sum_{j}^{J} Y3_{pkjt} \geq \sum_{j}^{J} Z_{pjkt-1}.S1_p - d_4.\left(\sum_{j}^{J} Z_{pjkt-1} - \lambda_2\right) - M.\pi_6 \qquad \forall p, \forall k, \forall t$$

**Constraint type-3:** Fuzzy non-linear constraints whose right hand value involves only one fuzzy parameter (6.25), (6.26), (6.30), (6.31), (6.32) and (6.33). For instance, constraint (6.25):

$$IW_{pj1} - SV1_{pj1} \leq M.(1 - Q1_{pj1}) \qquad \forall p, \forall j$$

$$IW_{pj1} \leq M.Q1_{pj1} \qquad \forall p, \forall j$$

$$IW_{pj1} \geq SV1_{pj1} \qquad \forall p, \forall j$$

$$SV1_{pj1} \leq IW_{pj0} - DW_{pj1} + d_{12}.(1-\lambda_1) - \sum_{k}^{K} Z_{pjk1}$$

$$SV1_{pj1} \leq IW_{pj0} - DW_{pj1} + d_{12}.(1-\lambda_2) + M.\pi_{14} - \sum_{k}^{K} Z_{pjk1}$$

$$SV1_{pj1} \geq IW_{pj0} - DW_{pj1} - d_{12}.(1+\lambda_1) - \sum_{k}^{K} Z_{pjk1}$$

$$SV1_{pj1} \geq IW_{pj0} - DW_{pj1} - d_{12}.(1+\lambda_2) - M.\pi_{15} - \sum_{k}^{K} Z_{pjk1}$$

### *6.5.3 Werner's Approach Fuzzy-and Operator*

Werner (1987) proposed the *fuzzy-and* operator approach which is the convex combination of min operator and arithmetical mean. Werner's *fuzzy-and* operator approach has the advantage of being a strongly monotonically increasing function that is a performance criterion for evaluating the compensatory operators (Topaloğlu and Selim, 2010).

In the study of Tiryaki (2006), a computationally efficient compensatory fuzzy aggregation operator, Werners' compensatory "*fuzzy-and*'' operator method is used for solving the decentralized multi-level linear programming problem. According to that study, this approach is more appropriate than the other computational efficient compensatory fuzzy operators in the literature. Because, this approach efficiently generates a wider set of compensatory compromise solutions which are also Pareto-optimal solutions for decentralized multi-level linear programming problem, based on the compensation parameter γ.

In the Werner's approach, the fuzzy set decision is determined by the following membership function and the following linear programming model can be obtained for the solution.

$$\mu_D(x) = \gamma . min_{k=1}^{K} \mu_k(x) + (1-\gamma).\frac{1}{K}.\sum_{k=1}^{K} \mu_k(x) \tag{6.47}$$

$$\max \ \gamma.\lambda + (1-\gamma).\frac{1}{K}.\sum_{k=1}^{K} \lambda_k$$

$$S.t. \qquad \mu_k(x) \geq \lambda + \lambda_k \qquad \forall k, \forall x \in X$$

$$\lambda, \lambda_k, \gamma \in [0,1] \tag{6.48}$$

Where $K$ is the total number of fuzzy objective(s) and constraint(s), $\mu_k(x)$ is the membership function of the fuzzy sets, and γ is the coefficient of compensation taking value within the interval [0,1]. For γ=1, the fuzzy-and operator becomes the min-operator; for γ=0, behaves as the arithmetic average of the fuzzy constraints (Bilgen, 2010b, 2008).

By using the formulations defined in (6.48), the auxiliary model of the FMTP problem can be explained by using Werner's approach with the addition of the non-fuzzy constraints. Again, summary of the transformation process for stated problem by using *fuzzy-and* Operator is given in Table 6.3.

Table 6.3 Summary of the transformation process for stated problem by using Werner's approach fuzzy-and operator

| |
|---|
| **Objective:** max $\gamma.\lambda + (1-\gamma).\frac{1}{18}.\sum_{k=1}^{18}\lambda_k$ |
| $Total\ cost\ of\ the\ CLSC \ \leq\ z_0 + d_0.(1-\lambda-\lambda_1)$ |
| **Constraint type-1:** Fuzzy linear constraints whose right hand value consists of only one parameter (6.9), (6.10), (6.12), (6.15), (6.16), (6.21), (6.22) and (6.29). For instance, constraint (6.9): |
| $\sum_{p=1}^{P} X_{pit}.Pt_{pi} \leq AP + d_1.(1-\lambda-\lambda_2) \qquad \forall i, \forall t$ |
| **Constraint type-2:** Fuzzy linear constraints whose right hand value is equal to multiplication of a fuzzy parameter by a variable or summation of variables (6.13), (6.17) and (6.19). For instance, constraint (6.13): |
| $\sum_{l}^{L} Y2_{pklt} + \sum_{j}^{J} Y3_{pkjt} \ \geq\ \sum_{j}^{J} Z_{pjkt-1}.S1_p - d_4.\left(\sum_{j}^{J} Z_{pjkt-1} - \lambda - \lambda_6\right) \qquad \forall p, \forall k, \forall t$ |
| **Constraint type-3:** Fuzzy non-linear constraints whose right hand value involves only one fuzzy parameter (6.25), (6.26), (6.30), (6.31), (6.32) and (6.33). For instance, constraint (6.25): |
| $IW_{pj1} - SV1_{pj1} \leq M.(1 - Q1_{pj1}) \qquad \forall p, \forall j$ |
| $IW_{pj1} \leq M.Q1_{pj1} \qquad \forall p, \forall j$ |
| $IW_{pj1} \geq SV1_{pj1} \qquad \forall p, \forall j$ |
| $SV1_{pj1} \leq IW_{pj0} - DW_{pj1} + d_{12}.(1-\lambda-\lambda_{13}) - \sum_{k}^{K} Z_{pjk1}$ |
| $SV1_{pj1} \geq IW_{pj0} - DW_{pj1} - d_{12}.(1+\lambda+\lambda_{13}) - \sum_{k}^{K} Z_{pjk1}$ |

In this method, a balance point can be found between the min operator value and the arithmetic mean value of all fuzzy constraints. As mentioned previously, according to the value of the γ, fuzzy-and operator acts like min operator or arithmetic average of the fuzzy constraints or a balancing position may be found.

### *6.5.4 Li's Two-Phase Approach*

Generally, determination of the compensatory coefficient γ is difficult. Also, the solutions obtained by the compensatory operators are not efficient sufficiently. Thus, Li (1990) proposed the two-phase approach with equal weighted coefficients to generate a compensatory and efficient solution for solving multiple objective linear programming problems (Guu and Wu, 1997; Topaloğlu and Selim, 2010). In other words, max-min approach does not guarantee the fuzzy efficient compromise solution. Therefore, in the first phase, a solution is generated by using Zimmermann's min operator, and then in the second phase, this solution and the average operator (arithmetic mean value of all memberships) are used to for improving the solution. Thus, a better solution which is called the fuzzy efficient compromise solution is obtained in the second phase.

Optimal solution obtained by the first phase may not be an efficient solution in the sense that there may exist another solution in the feasible space dominating the obtained solution by the max–min method (Mahdavi, Javadi, Sahebjamnia, and Amiri 2009). However, Li's two phase approach does not take into account the relative weights of the fuzzy objective(s) and constraints (Karmakar and Mujumdar, 2007). It means that equally weighted coefficients are used in the second phase. The mathematical programming of this efficient compromise solution is given as follow;

$$\max \ \sum_{k=1}^{K} \lambda_k / K$$

$$\lambda \leq \lambda_k \leq \mu_k(x) \qquad \forall k, \forall x \in X$$

$$\lambda, \lambda_k \in [0,1] \qquad (6.49)$$

Where $\lambda$ is the solution of max-min method. By using the mathematical formulation given in inequalities (6.49), the transformed model of the FMTP problem can be explained by using Li's two phase approach with the addition of the non-fuzzy constraints. Table 6.4 summarizes the application procedure.

Table 6.4 Summary of the transformation process for the stated problem by using Li's two-phase approach

**Objective:** max $\frac{1}{18}.\sum_{k=1}^{18}\lambda_k$

$Total\ cost\ of\ the\ CLSC\ \leq\ z_0 + d_0.(1-\lambda_1)$

**Constraint type-1:** Fuzzy linear constraints whose right hand value consists of only one parameter (6.9), (6.10), (6.12), (6.15), (6.16), (6.21), (6.22) and (6.29). For instance, constraint (6.9):

$$\sum_{p=1}^{P} X_{pit}.Pt_{pi} \leq AP + d_1.(1-\lambda_2) \qquad \forall i, \forall t$$

**Constraint type-2:** Fuzzy linear constraints whose right hand value is equal to multiplication of a fuzzy parameter by a variable or summation of variables (6.13), (6.17) and (6.19). For instance, constraint (6.13):

$$\sum_{l}^{L} Y2_{pklt} + \sum_{j}^{J} Y3_{pkjt} \geq \sum_{j}^{J} Z_{pjkt-1}.S1_p - d_4.\left(\sum_{j}^{J} Z_{pjkt-1} - \lambda_6\right) \forall p, \forall k, \forall t$$

**Constraint type-3:** Fuzzy non-linear constraints whose right hand value involves only one fuzzy parameter (6.25), (6.26), (6.30), (6.31), (6.32) and (6.33). For instance, constraint (6.25):

$$IW_{pj\,1} - SV1_{pj\,1} \leq M.(1-Q1_{pj\,1}) \qquad \forall p, \forall j$$

$$IW_{pj\,1} \leq M.Q1_{pj\,1} \qquad \forall p, \forall j$$

$$IW_{pj\,1} \geq SV1_{pj\,1} \qquad \forall p, \forall j$$

$$SV1_{pj\,1} \leq IW_{pj\,0} - DW_{pj\,1} + d_{12}.(1-\lambda_{13}) - \sum_{k}^{K} Z_{pjk\,1}$$

$$SV1_{pj\,1} \geq IW_{pj\,0} - DW_{pj\,1} - d_{12}.(1+\lambda_{13}) - \sum_{k}^{K} Z_{pjk\,1}$$

**Additional Constraints:** $\lambda \leq \lambda_k \leq 1 \qquad \forall k$

This model can be solved after yielding the auxiliary variable value of $\lambda$ from the solution of max-min method. This value forms a lower bound for all membership functions' values.

## 6.6 Application of the Proposed FMTP Model to an Illustrative Example

The application of the proposed fuzzy mathematical model is illustrated through a basic example for depicting the validity and practicality. The following data are used for presenting the multi-echelon, multi product, multi-period MTP model of a hypothetical CLSC:

Table 6.5 Information related to the size of test problem

| | **Size of the FMTP problem** |
|---|---|
| Number of conceptual product types | 2 |
| Number of manufacturing plants | 2 |
| Number of wholesalers | 3 |
| Number of retailers | 6 |
| Number of collection centers | 2 |
| Number of remanufacturing facilities | 2 |
| Number of time periods (in weeks) | 8 |

- The storage costs for a unit of any type of finished product at the manufacturing plants and wholesalers are $1.6 and $1.7 per unit per week. Similarly, unit inventory holding costs of returned products at the collection centers and remanufacturing facilities are $1.5, $1.6, $1.6 and $1.7, respectively. Inventory carrying costs of the remanufactured products at the remanufacturing facilities are $1.65 and $1.75 per unit per week. Finally, inventory holding costs of returned products at the wholesalers are $1.7 and $1.8 per unit per week for each product type.
- The tardiness costs per unit of product type 1 and 2 that arrive late at the wholesalers and the retailers are $100, $150, $150 and $170, respectively.
- The penalty costs for never delivering one unit of product type 1 and 2 to the retailer and to the wholesaler at the end of the planning horizon (At the end of week 8) are $300 and $320, respectively.
- Unit collection costs for the returned products to the collection centers and wholesalers are $1.5 and $2 for product type 1 and 2, respectively.
- Disposal costs for the used products that are not in a good condition for the remanufacturing operations are $1 and $1.2 for the scrap product type 1 and 2, respectively.
- The distances between several stages in the CLSC take the value of interval 10-80 kilometers.
- Assuming the boundary conditions; initial tardy products and starting inventory levels ($IM_{pi0}$, $IC_{pl0}$, $IW1_{pj0}$, $IW_{pj0}$, $IR1_{pr0}$ and $IR2_{pr0}$) are equal to zero. All other parameters are given in the Tables 6.6, 6.7 and 6.8.

Product information such as unit transportation costs, production costs, remanufacturing costs; unit production and remanufacturing times at each manufacturing plant and remanufacturing facility are given in Table 6.6.

Table 6.6 Product information

| Prod. Type | Transportation cost for new/used products per unit per kilometer | Production cost at plant 1/2 | Remanufacturing cost at facility 1/2 | Production time at plant 1/2 | Remanufacturing time at facility 1/2 |
|---|---|---|---|---|---|
| 1 | $0.0015/$0.002 | $30/$40 | $8/$10 | 0.1h/0.12h | 0.05h/0.05h |
| 2 | $0.002/$0.003 | $20/$50 | $6/$13 | 0.15h/0.1h | 0.07h/0.06h |

The demand forecasts belong to the wholesalers (W) and the retailers (R) for these two different types of products (P1 and P2) are presented in the Table 6.7. Also, it is accepted that there may be ∓ %10 deviations from the retailers' demands and ∓ %5 deviations from the wholesalers' demands. Because, at the lower levels of the supply chain, variability and uncertainty state of the demand forecasts are more prevalent. Therefore, the upper and lower limit values of demands and tolerance values are calculated through the multiplication of the wholesalers' demand values with 0.95, 1.05 and 0.05 and retailers' demand values with 0.9, 1.10 and 0.10.

Desired levels and tolerance values for the goal and the other parameters regarding fuzzy constraints such as maximum capacity values, available time for production and remanufacturing, return fractions, acceptance ratios and transportation upper bounds are given in Table 6.8.

Table 6.7 Weekly demand forecasts for the wholesalers and retailers over the planning horizon

| | Week 1 | Week 2 | Week 3 | Week 4 | Week 5 | Week 6 | Week 7 | Week 8 |
|---|---|---|---|---|---|---|---|---|
| W1-P1 | 0 | 280 | 270 | 240 | 360 | 250 | 290 | 260 |
| W1-P2 | 0 | 320 | 230 | 360 | 310 | 240 | 350 | 270 |
| W2-P1 | 0 | 250 | 290 | 380 | 330 | 280 | 290 | 330 |
| W2-P2 | 0 | 230 | 240 | 280 | 200 | 290 | 200 | 360 |
| W3-P1 | 0 | 300 | 260 | 330 | 320 | 220 | 200 | 270 |
| W3-P2 | 0 | 240 | 320 | 370 | 200 | 370 | 240 | 260 |
| R1-P1 | 0 | 100 | 140 | 80 | 110 | 170 | 110 | 190 |
| R1-P2 | 0 | 70 | 170 | 120 | 100 | 190 | 200 | 110 |
| R2-P1 | 0 | 100 | 120 | 120 | 170 | 180 | 150 | 70 |
| R2-P2 | 0 | 190 | 80 | 150 | 90 | 160 | 170 | 100 |
| R3-P1 | 0 | 110 | 180 | 170 | 180 | 130 | 190 | 110 |
| R3-P2 | 0 | 170 | 130 | 180 | 190 | 140 | 140 | 80 |
| R4-P1 | 0 | 160 | 170 | 90 | 90 | 150 | 180 | 70 |
| R4-P2 | 0 | 120 | 130 | 100 | 70 | 140 | 90 | 140 |
| R5-P1 | 0 | 170 | 110 | 90 | 150 | 140 | 130 | 130 |
| R5-P2 | 0 | 190 | 80 | 120 | 120 | 170 | 90 | 80 |
| R6-P1 | 0 | 120 | 90 | 140 | 180 | 120 | 200 | 140 |
| R6-P2 | 0 | 100 | 120 | 170 | 70 | 190 | 140 | 200 |

Table 6.8 Desired levels and tolerance values

| | **$b_i$ (Target value)** | **$d_i$ (Tolerance value)** |
|---|---|---|
| $z_0$ | \$560000 | \$200000 |
| $AP$ | 126h | 42h |
| $AR$ | 126h | 42h |
| $UB_{pi}$ | Range of 1200-1270 units | 180-190 units |
| $UB1_{pr}$ | Range of 1150-1250 units | 172-187 units |
| $S1_p$ | %70-%75 | %30 |
| $S2_p$ | %80-%85 | %30 |
| $CR_p$ | %80 | %20 |
| $RCAP_{pr}$ | Range of 450-580 units | 67-87 units |
| $CCAP_{pl}$ | Range of 300-350 units | 45-52 units |
| $WCAP_{pj}$ | Range of 300-390 units | 45-58 units |

ILOG OPL Studio version 6.3 including CPLEX 12.1.0 product is used to solve the transformed fuzzy mathematical programs on an Intel Core i7 2 GHz PC by making use of the above defined data. Solutions which are obtained from ILOG OPL software are summarized in Table 6.9. No additional parameter settings are used in CPLEX. According to the comparison of the results for crisp model and fuzzy models, all fuzzy models provide a better objective function value than the crisp MIP model due to its flexibility in handling constraints. However, proposed crisp model is better than the fuzzy models in terms of solving time due to the requirement of less CPU time for the solution. In addition, all of the four aggregation operators used have provided satisfactory results.

Table 6.9 Summary of the results obtained by different fuzzy mathematical programming approaches

| **MIP results** | **Crisp** | **Zimmermann's max-min method** | **Zimmermann's convex combination of min and max operator** | **Werner's Approach Fuzzy-and Operator** | **Li's two-phase approach** |
|---|---|---|---|---|---|
| Total number of variables | 1855 | 2041 | 2073 | 2060 | 2059 |
| Total number of integer variables | 1184 | 1184 | 1184 | 1184 | 1184 |
| Total number of binary variables | 246 | 246 | 277 | 246 | 246 |
| Total number of constraints | 1412 | 1875 | 2794 | 1894 | 1912 |
| Total number of iterations | 694 | 198881 | 227218 | 45370 | 3188 |
| Solving time (sec.) | 0.89 | 110.3 | 133.7 | 131.05 | 0.72 |
| Total cost | $638566 | $591660 | $591100 | $583700 | $586910 |
| Fuzzy parameters | - | λ=%84,17 | λ=%84,4 | λ=%88,15 | λ=%86,54 |

However, outcomes display that Werner's approach (fuzzy and operator) and Li's two phase approach yield better solutions than the others although not much difference exists between them.

Among the fuzzy models, Zimmermann's convex combination of min and max operator requires more variables and constraints for the transformation process. For this reason, time to solve this model is larger. Similar results are reported by (Bilgen, 2010a, 2010b) for comparing the usage of different aggregation operators in different problem types. In this Chapter, Werner's approach (fuzzy and operator) is used to present some additional model results as shown in Table 6.10 and Figures 6.6 and 6.7 since this approach provides better results in terms of total CLSC costs.

In the final solution of Werner's approach, $\lambda$ is equal to 0.8815 which means that fuzzy membership functions mentioned previously are satisfied %88,15 at least. According to the results, production and remanufacturing quantities during each week are obtained as shown in Table 6.10.

Table 6.10 Production/remanufacturing quantities in manufacturing plants/remanufacturing facilities

| | **Manufacturing Plant-1** | | **Manufacturing Plant-2** | | **Remanufacturing Facility-1** | | **Remanufacturing Facility-2** | |
|---|---|---|---|---|---|---|---|---|
| Week | Type-1 | Type-2 | Type-1 | Type-2 | Type-1 | Type-2 | Type-1 | Type-2 |
| 1 | 1221 | 1292 | 863 | 735 | 0 | 0 | 0 | 0 |
| 2 | 1220 | 1292 | 145 | 165 | 0 | 0 | 0 | 0 |
| 3 | 0 | 0 | 0 | 0 | 867 | 782 | 1180 | 337 |
| 4 | 0 | 0 | 0 | 0 | 869 | 848 | 1180 | 318 |
| 5 | 0 | 0 | 0 | 0 | 868 | 646 | 1180 | 379 |
| 6 | 0 | 0 | 0 | 0 | 868 | 475 | 1179 | 174 |
| 7 | 0 | 0 | 0 | 0 | 854 | 0 | 885 | 0 |
| 8 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

Most of the wholesalers' and retailers' demand are satisfied by remanufacturing facilities after week 2 since returned products can first arrive the remanufacturing facilities at week 2. Also, this way is more profitable than production in order to meet customers demand. Total transportation quantities of new product type 1 and 2 from the manufacturing plants to wholesalers, remanufactured product type 1 and 2 from the remanufacturing facilities to the wholesalers and then wholesalers to the retailers, over the planning period are depicted in Figure 6.6.

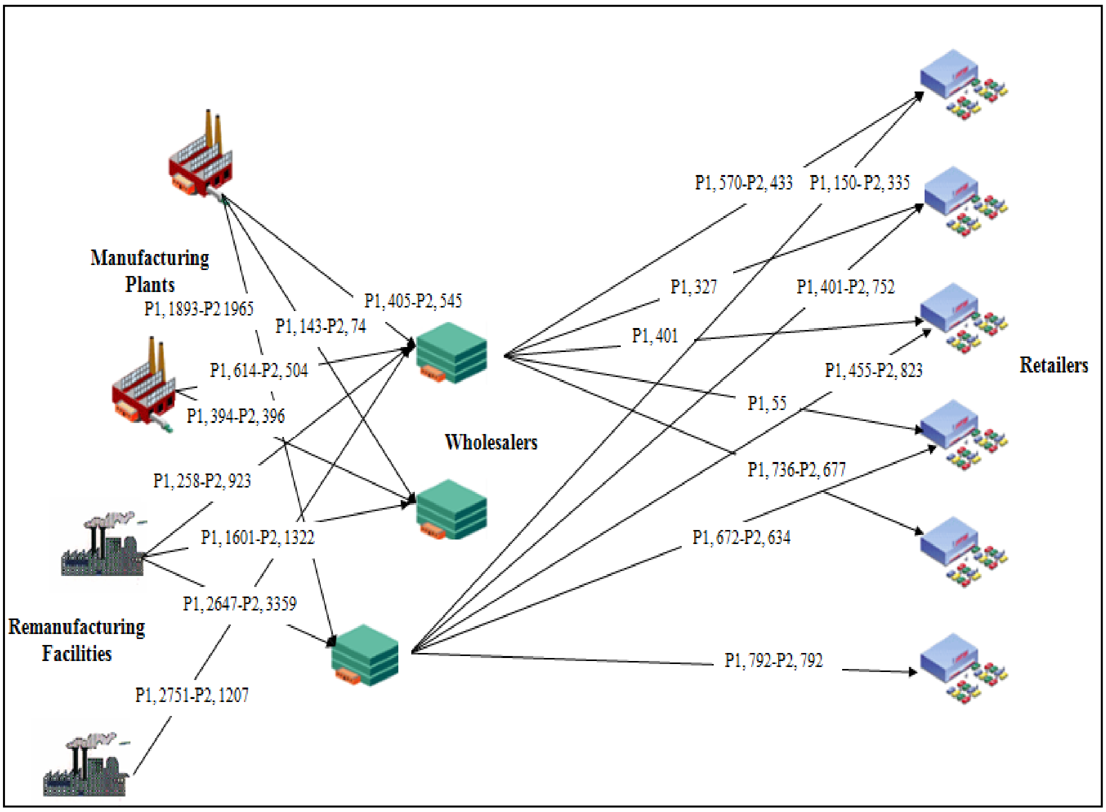



Figure 6.6 Total transported quantities related to product type 1 and 2 over the planning horizon in the forward supply chain

When looked at the forward flows in the CLSC, none of the retailers' demand satisfied by the wholesaler 2 since there aren't outgoing flows from this wholesaler. Because, this wholesaler farthest one from the retailers. It means that all of the incoming flows to this wholesaler only meet its demand not the retailers' demand. For the similar reason, remanufacturing facility 2 only serves to the wholesaler 1. Total transportation quantities of collected scrap product type 1 and 2 from the retailers to collection centers, then from collection centers to remanufacturing facilities, quantities of returned product type 1 and 2 from the retailers to the wholesalers as well as directly from the end customers to the wholesalers and then to the remanufacturing facilities, over the planning horizon are depicted in Figure 6.7.

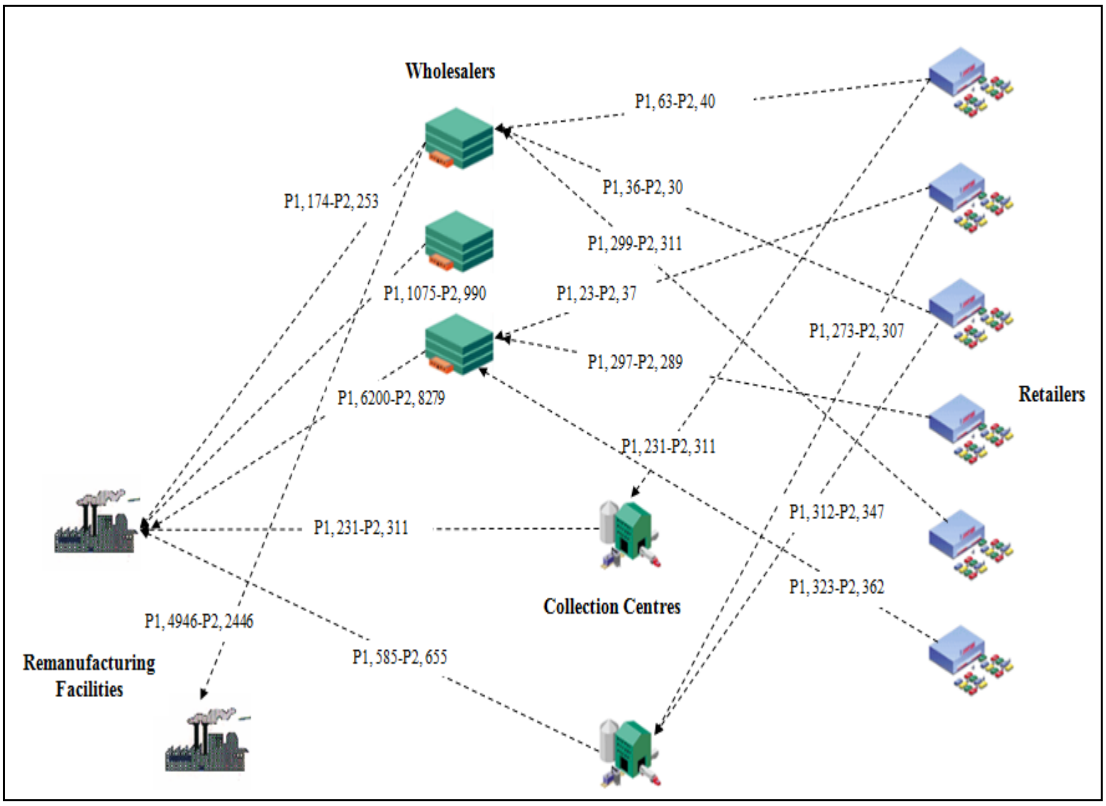



Figure 6.7 Total transported quantities related to used product type 1 and 2 over the planning horizon in the reverse supply chain

When looked at the reverse flows in the CLSC, there are no incoming flows to wholesaler 2 again. In other words, none of the used scrap products are collected from the retailers by this wholesaler. As mentioned earlier, this wholesaler is farthest one from the retailers. Thus, only the uncertain fraction of this wholesaler's demand returned to it. For the similar reason, only the wholesaler 1 sends the returned products to the remanufacturing facility 2.

## 6.7 Scenario Analysis

In order to analyze the sensitivity of the decision parameters and gain managerial insights regarding collection-remanufacturing system to variation of satisfaction degree related to the Werner's fuzzy model, the proposed FMTP model are resolved with different target values of acceptance ratio (%), unit remanufacturing cost ($), transportation upper bounds of remanufactured products (units) and weekly available time for remanufacturing (hours), respectively.

Scenario analysis is applied in four different scenarios by using the application data as it can be seen in Table 6.11.

Table 6.11 Application data of the four scenarios

| **Scenario** | **Item** | **Run 1** | **Run 2** | **Run 3** |
|---|---|---|---|---|
| Scenario 1 | $CR_p$ | Low (%30) | Medium (%60) | High (%90) |
| Scenario 2 | $RC_{pr}$ | $5 | $15 | $25 |
| Scenario 3 | $UB1_{pr}$ | 500 units | 1000 units | 2000 units |
| Scenario 4 | $AR$ | 80 h | 120 h | 150 h |

Application of the four scenarios with three runs in Werner's fuzzy model yields the following satisfaction degrees and total costs as depicted in Figures 6.8 and 6.9. Figures 6.8 and 6.9 display that when the acceptance ratio increases, satisfaction degree of the fuzzy model will increase dramatically. Similarly, increments in transportation upper bounds and weekly available time for remanufacturing provide better results. On the other hand, accretion in unit remanufacturing cost has a negative effect on both satisfaction degree and total CLSC cost. In other words, it causes cost increments from $559670 to $750000.

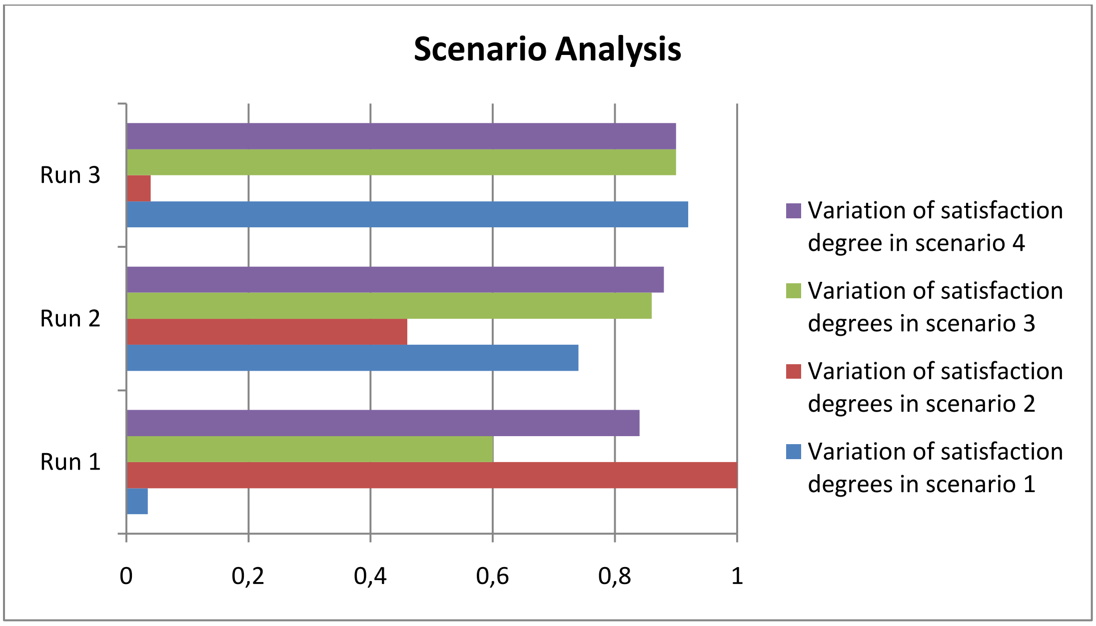



Figure 6.8 Variation of satisfaction degrees as a result of all scenarios

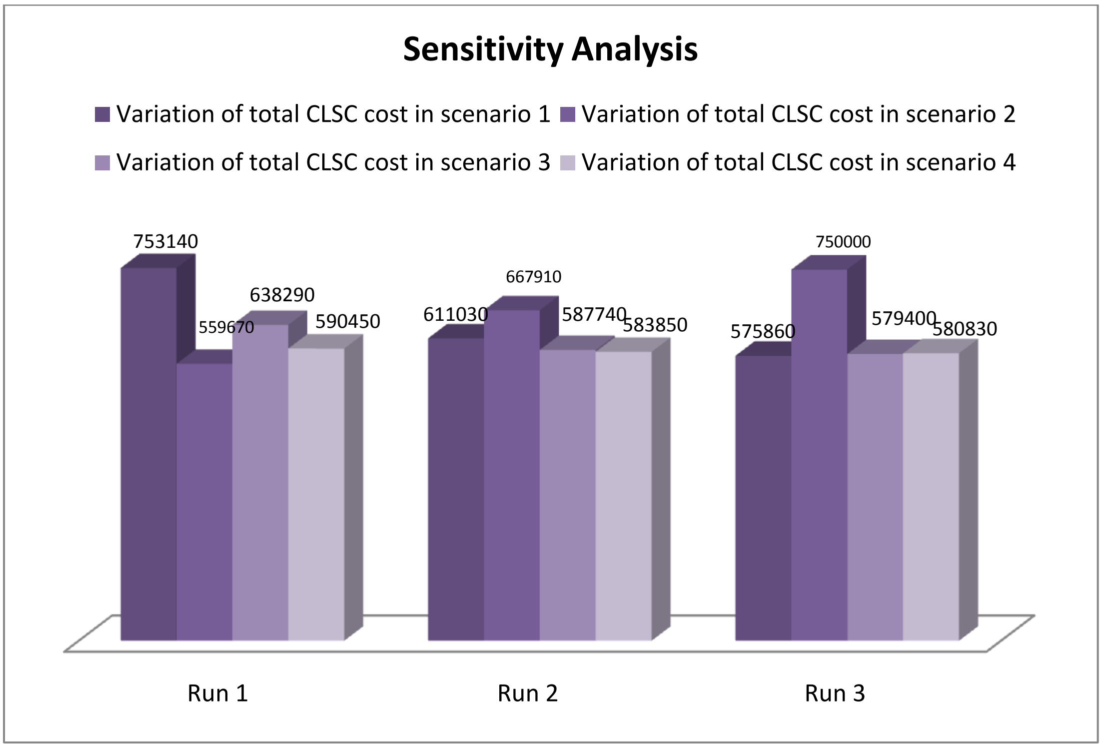



Figure 6.9 Variation of total CLSC costs as a result of all scenarios

### 6.8 Chapter Conclusion and Future Studies

Due to aforementioned factors such as environmental, governmental and economic, CLSC planning in tactical level should be intertwined by manufacturing firms and other stakeholders considering the recovery activities and they also have to integrate the forward supply chain with the reverse supply chain while preparing their medium-term planning activities.

In this case, the complexity of the planning model will be increased due to the additional reverse flows. In this Chapter, a mixed integer programming model which includes non-linear constraints for the CLSC of a conceptual product is developed to determine the production levels for each type of product in each manufacturing plant, distribution and inventory levels for each type of product in each wholesaler, the level of tardy and number of products not delivered in each time period, disposal level and remanufacturing level at different remanufacturing facilities with the objective of minimizing the total CLSC costs.

Due to the ambiguity in determining some of the parameters such as capacity, return fraction, acceptance ratio and demand in the real life CLSCs, fuzzy mathematical programming approach is employed in model development. The fuzzy model is transformed into a crisp equivalent model by making use of different aggregation operators and fuzzy solution approaches from the literature. The final crisp model is solved by using the standard branch and bound technique via optimization solver of ILOG OPL Studio 6.3 for an example problem. The proposed model will be extended to a model with multiple objectives and development of a meta-heuristic solution approaches for larger size problems are also scheduled as future works.

# CHAPTER SEVEN
# CONCLUSIONS AND CONTRIBUTIONS

## 7.1 Summary

Due to the three main drivers of RL and CLSCs; environmental, economical issues and legal obligations, there has been a growing interest in RL, recycling, remanufacturing and reusing. For this reason, novel mixed integer linear programming models were developed for complex strategic CLSC network design and tactical planning under crisp and fuzzy environments. In addition to the conclusion parts of each Chapter where the developed mathematical models are stated, following paragraphs present a general summary of this thesis.

In Chapter 4 (Model I), since addressing the strategic planning problem is crucial for the lead/acid battery sector and the rarely discussion of multi-objective RL & CLSC network design models in the literature; a multi-objective, multi-echelon and multi-product mixed integer linear programming model with different importance and priorities is developed in fuzzy environment.

In Chapter 5 (Model II), a holistic modelling approach is presented for a tire CLSC via mixed integer linear programming. Main alternative recovery options in tire industry such as remanufacturing, recycling and energy recovery are considered simultaneously in the proposed model. Briefly, a multi-objective, multi-echelon, multi-product and multi-period logistics network design model is formulated while taking into account the environmental issues by eco-indicator 99 methodology.

In Chapter 6 (Model III), after developing two strategic planning models in earlier Chapters, a fuzzy mixed integer programming model for medium-term planning in a CLSC related to a conceptual product with remanufacturing option is proposed. Involving tactical planning processes and fuzziness in all aspects of the problem are main features of that model.

## 7.2 Contributions

In this section, we distinguished the contributions of this thesis in three parts for Model I, II and III, respectively.

For Model I in Chapter 4, the following contributions are made:

1.) Since the lack of multi-objective optimization models in the literature of RL & CLSC network design problem, we dealt with an unhandled objective which is the maximization of the collection of returned batteries covered by the opened facilities based on the well known maximal coverage problem in the literature. To the best of our knowledge, this objective has not been addressed by the previous works so far and very necessary and vital in the case of scarce financial resources for different performance measurements such as customer satisfaction from the reverse operations (reverse service level), responsiveness of the CLSC network, maximum economical benefits obtained from the recovery and environmental effectiveness.

2.) This study presents the first application of the method developed by Chen and Tsai (2001) for FGP-DIP in RL and CLSC management where the aspiration levels of the objectives are stated as fuzzy. Thus, a new application area for this method is revealed. Apart from the other applications of this method, in order to produce better decisions than individual decision making and reducing the effects of individual bias, desirable achievement degree of each fuzzy goal is determined in a group decision making environment. A new approach for obtaining the desirable achievement degree of each fuzzy goal is proposed in group decision making environment where the importance/weights and the index of optimism of each group member are different.

3.) New flexibility criteria namely total recycling and collection volume flexibility are added to the third objective function, total volume flexibility, as an important component due to the nature of reverse flows in RL & CLSC network design problem.

4.) A real life decision making situation in lead/acid battery industry related to the purchasing and selling of spent batteries to the scrap dealers are taken into account in the mathematical model development phase.

5.) In lead/acid battery sector, decisions related to the types of the facilities such as distribution, collection or hybrid that will be opened is as important as where they will be located. Therefore, in addition to determine the facility locations, facility type is also considered in the proposed model for the candidate locations.

The main contributions of the Model II in Chapter 5 are described as follows:

1.) The mathematical model that is proposed in Chapter 5 beyond the literature since including wide range of modeling characteristics or features for RL & CLSC network design. Thus, better reflection of real life applications can be provided via the proposed model.

2.) In contrast to the other studies in the literature, Chapter 5 presents more holistic view to a tire CLSC with its both profit and ecologically oriented mathematical model.

3.) Eco-indicator 99 method is generally used for traditional forward chemical supply chain network design and planning in the literature. However, we used this technique for a CLSC network design based on a tire recovery case.

4.) Since the sensitivity analysis cannot be applied directly to the mixed integer programming models, Taguchi DOE approach is employed in order to reach the optimum objective values that are targeted and examine the effects of some parameters' values on the objective functions. In other words, in order to provide the best objective function values and analyze the effects of major factors, an alternative analyzing method which is based on Taguchi experimental design technique is applied. Besides the individually effects, simultaneous parameter effects can also be analyzed via the interaction plots by using this technique. To the best of our knowledge, there is no other study which uses this advanced quality improvement method for the aforementioned purposes in the literature so far.

For model III in Chapter 6, the following contributions are made:

1.) There are lots of studies in the literature related to the RL & CLSC network design problem which takes place in strategic planning level but a few of them handles the tactical planning activities. Thus, Chapter 6 focused on the modelling of a generic medium term planning problem in a CLSC while considering most commonly encountered product recovery option “remanufacturing”. Therefore, a mixed integer programming model which includes non-linear constraints is developed for CLSC planning at the tactical level.

2.) Production-distribution planning process is more complex when recovery options are involved because of the complicating characteristics such as uncertainty in timing, quality and quantity of returned products as discussed by Guide Jr. (2000). For this reason, in the proposed model return rate and acceptance ratio (for the unknown condition of the returned products) are also considered as fuzzy in order to overcome this drawback (uncertainty in quality and quantity of returned products).

3.) In real life applications, companies should take into account the recovery options while preparing their medium-term plans instead of using traditional production planning models. The integration of these recovery options into the medium-term planning procedures is pre-requisite for the enterprise firms for an efficient planning and their sustainable development in competitive markets.

## 7.3 Future Works

Suggestions for future researches based on the developed models in Chapter 4, 5 and 6 are stated as follows:

- Development of heuristic solution approaches for larger size problems is scheduled as a future work for Model I. Furthermore, an extended model may be proposed by adding multi-period, multi-mode transportation in network design concept. In addition, other FGP techniques can be used for comparison of the model results in the future research.
- In addition to the uncertainty in environmental parameters, uncertainty related to the demand of new and retreaded tires, return quantities of the end of life tires, return rates and capacities (for both facilities and vehicles) may be overcome with fuzzy mathematical programming approach in the future researches for model II. Moreover, environmental results obtained from the used LCA based approach, eco-indicator 99, may be compared with the other techniques' results such as carbon footprint methods.
- In future, since the model III in Chapter 6 is considered for single objective, the multi-objective model which approaches the problem with the environmental and social aspects may be considered. Thus, development of a sustainable tactical planning model can be scheduled as a future work.
- In general, multi agent systems may be developed for dynamic supply chain network design and planning problems instead of solving the static versions of these problems.

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