Multi-objective Design and Optimization of a Closed-loop Supply Chain Network, and Assessment of Collection Methods, Product Recovery Methods and Network Configurations

THESIS

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......dedicated

to

my beloved parents......

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CERTIFICATE

This is to certify that the thesis entitled **"Multi-objective Design and Optimization of a Closed-loop Supply Chain Network, and Assessment of Collection Methods, Product Recovery Methods and Network Configurations"** submitted by **Anil Jindal,** ID. No. **2008PHXF424P** for the award of PhD Degree of the Institute embodies the original work done by him under my supervision.

Signature in full of the Supervisor ________________________________

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ABSTRACT

Closed-loop supply chain (CLSC) has gained increasing attention among supply chain management researchers and practitioners because of growing concerns towards green manufacturing and sustainable development. CLSC entails combine forward supply chain and reverse supply chain activities into a single system, with the potential to raise the environmental performance and to create new profit opportunities. The effectiveness of CLSC depends on the network design and optimization of the underlying supply chain. Moreover, it is complicated by uncertainty in its underlying variables viz. quantity, quality and time of product return.

Dealing with uncertainty in CLSC network design has vital importance for the firms. Literature in provides different CLSC models considering different set of product recovery options, different set of cost, different set of binary variables and different set of uncertain parameters. Therefore, there is a need to design and optimize a generalized closed-loop supply chain model that considers the different costs, different product recovery options, and uncertain parameters, to make the design more pragmatic.

So, the purpose of thesis is to design and optimize a multi-product, multi-time, multi-echelon capacitated closed-loop supply chain network in an uncertain environment. A fuzzy mixed-integer linear programming model is developed to maximize the profit of organization.

With the increasing concern for environmental degradation, the single objective CLSC is not sufficient; therefore, a multi-objective CLSC model is proposed in this thesis that considers the both maximization of profit and minimization of environmental impact. The ϵ-constraint method is used to solve the multi-objective CLSC model.

Other than network design and optimization, effective CSLC implementation needs strategic decision-making regarding selection of collection methods, selection of product recovery process, and selection of network configuration. Therefore, this thesis also aims at developing integrated fuzzy multi-criteria decision-making models (Fuzzy AHP + TOPSIS) for the assessment and evaluation of collection methods, product recovery processes and network configurations under the inherent uncertainty of reverse logistics.

Significance of this study is that it will help the organizations for strategic decision-making model to implement reverse logistics. The generalized closed-loop supply chain network and optimization model will help the organizations to find the optimal number of products to be remanufactured and the optimal number of parts to be purchased from external suppliers. This research also provides a toolkit to managers for the optimal location and allocation to different collection centers, disassembly centers, refurbishing centers and external suppliers. Integrated fuzzy multi-criteria decision-making models in this research will also help organizations to prioritize and develop the collection, product recovery and network facilities accordingly.

This study also has significance for researchers working in the field of reverse logistics and other similar areas as it provides an exhaustive literature review and research gaps in the existing network model of reverse logistics.

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LIST OF SYMBOLS AND ABBREVIATIONS

Symbol/ Abbreviation	Description
AHP	Analytic Hierarchy Process
CLSC	Closed-loop Supply Chain
DEA	Data Envelopment Analysis
DM	Decision Makers
ELVs	end-of-life vehicles
GA	Genetic Algorithm
GP	Goal Programming
ISM	Interpretive Structural Programming
LiB	Lithium-ion BAttery
LP	Linear Programming
MCDM	Multi-criteria Decision Making
MILP	Mixed-integer Linear Programming
MINLP	Mixed-integer Non Linear Programming
MIP	Mixed Integer Programming
OEM	Original Equipment Manufacturer
OLSC	Open-loop Supply Chain
PSO	Particle Swarm Optimization
QFD	Quality Function Development
RL	Reverse Logistics
RSC	Reverse Supply Chain
TFN	Triangular Fuzzy Number
TOPSIS	Technique for Order Preference by Similarity to Ideal Solution

CHAPTER 1

INTRODUCTION

This chapter comprises the overview of reverse logistics, closed-loop supply chain, research motivation, research objectives, research methodology, significance the research, and outline of the thesis.

1.1. Overview of Reverse Logistics

Reverse logistics (RL) has gained increasing attention among researchers and practitioners of operation and supply chain management because of growing green concern, sustainable development, fierce global competition, future legislation, increased product return, environmentally consciousness of customers and so on. It is the process of planning, implementing and controlling backward flows of raw materials, in-process inventory, packaging and finished goods, from a manufacturing, distribution or use point, to a point of recovery or point of proper disposal (De Brito and Dekker, 2002). Design and implementation of reverse logistics is very different from forward logistics. The forward logistics include series of activities in the process of converting raw materials to finished products. Whereas reverse logistics is concerned about the recovery of returned products from customer to recovery point. The differences between forward and reverse logistics are presented in Table 1.1 (Min *et al.*, 2006; Pochampally *et al.*, 2009; Tibben-Lembke and Rogers, 2002).

Reverse logistics is a commonly used term in supply chain management. It may have a narrow or broad scope. The narrow scope of reverse logistics refers to the actual movement and management of reverse flows of products from customers to suppliers (Tibben-Lembke and Rogers, 2002), where the focus is on logistics issues such as transportation modes and routing (Kumar and Dao, 2006). The broader scope of RL include activities that support the management of used products including picking them up, sorting them out, and reusing them in different ways (Dowlatshahi, 2000).

Table 1.1 Differences between forward and reverse logistics

Characteristics	**Forward Logistics**	**Reverse Logistics**
Forecasting	Relatively straightforward	More difficult
Transportation	One to many	Many to one
Product quality	Uniform	Not uniform
Product packaging	Uniform	Often damaged
Destination/routing	Clear	Not clear
Disposition options	Clear	Not clear
Pricing	Relatively uniform	Depends on many factors
Costs	Directly visible	Less directly visible
Inventory management	Consistent	Not consistent
Marketing methods	Well-known	Complicated
Visibility of product/process	Clearly visible	Less visible
Priority	High	Low

Source: adopted and modified from Tibben-Lembke and Rogers (2002), Min *et al.*(2006) and Pochampally *et al.*(2009)

1.2. Overview of Closed-loop Supply Chain

Closed-loop supply chain (CLSC) is relatively new terminology that entails combining traditional forward supply chain activities and reverse supply chain activities into a single system (Krikke *et al.*, 2004), with the potential to raise the environmental performance of industrial operations to new standards, and to create new profit opportunities and competitive advantages for supply chain participants (Talbot *et al.*, 2007). The following are few of the benefits of CLSC (Talbot *et al.*, 2007):

- Improved product design and development opportunities.
- Improved competitiveness (acquisition of new R&D competencies, acquisition of new manufacturing and market competitiveness and increased profit).
- Improved manufacturing capabilities (new manufacturing technology, improved working condition, raw materials cost reduction, energy and cost reduction)

- Improved operational excellence (production, inventory and transportation cost reduction).
- Increased awareness of environmental technologies, reduction in legal fines and enhancement of corporate image.

Closed-loop supply chain has a number of benefits but a major issue in CLSC is the integration of information between the forward and reverse supply chain. To achieve optimum planning and reduction of costs the return information should be integrated with forward supply chain. It is further complicated by the uncertainty of quantity, quality and timing of product return (Guide *et al.*, 2000). In CLSC, the manufacturer needs to consider the manufacturing and remanufacturing activities together so as to meet the customer demand. The manufacturer needs to decide number of products to be remanufactured and number of parts to be purchased from external supplier to minimize the total cost. The whole CLSC network can be designed in such a way that it can increase company's profitability as well as company's environmental reputation. The research in closed-loop supply chain focuses mainly on reverse logistics and their integration with forward logistics, and less on the managing the forward supply chain.

1.3. Framework for Closed-Loop Supply Chain

The framework for closed-loop supply chain is to provide an overall understanding of supply chain. A framework is "a basic conceptional structure" to identify the different elements of closed-loop supply chain, to structure them, and to describe their relation to each other (Merriam-Webster, 2003).

Figure 1.1 represents a generalized framework for closed-loop supply chain containing both the forward and reverse supply chain. The upper part of figure with solid lines represents the forward supply chain, while the bottom part with dashed lines represents the reverse supply chain. Forward supply chain constitutes the external suppliers, manufacturer, distributor, retailer and customers. Reverse logistics starts with the collection of returned products from customers. Out of the returned products, the products which can be reused after minor repair are sent to distributor and the rest are forwarded to disassembly center to disassemble into parts. To check reusability of parts, sorting and testing is done parallel to disassembly. Here the parts are divided into different categories depending on their residual quality and different end-of-life options available, like refurbishable parts, recyclable parts and disposable parts. The parts which can be refurbished are sent to refurbishing center. The parts which have no value added recovery, but can be used for material recovery are sent to recycling center and the rest of parts are disposed off. Therefore the reverse logistics activities can be divided into three main stages, i.e. collection, inspection and sorting, and product recovery.

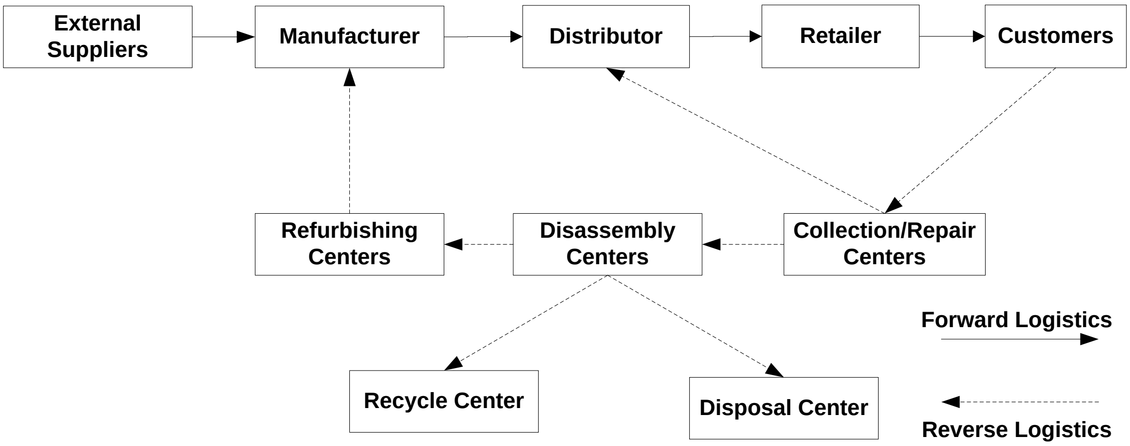

Figure 1.1 A generalized framework for closed-loop supply chain

Collection: Collection is the first and an important activity of reverse logistics. It refers to all activities rendering used products available and physically moving them to some point where further treatment is conducted for product recovery (Sasikumar and Kannan, 2008).

Inspection and sorting: Products after collection needs to be inspected and sorted. It consists of operations that determine whether a given product is reusable or not, and if yes, then to what extent. Inspection and sorting results in splitting the flow of used products according to distinct reuse or disposal options, e.g. distinguishing repairable and recyclable subassemblies of copiers (Krikke *et al.*, 1999).

Product recovery: Product recovery is an important activity of reverse logistics to manage the flow of products or parts destined for remanufacturing, repairing, or disposal and to effectively use the resources (Dowlatshahi, 2000). It is generally carried out to recover hidden economical value, to meet market requirements or to meet Government regulations (Sasikumar and Kannan, 2008). Some of the product recovery processes include repair, reuse, refurbish, remanufacture, cannibalize, recycle or disposal (Dowlatshahi, 2000; Thierry *et al.*, 1995).

1.4. Research Motivation

The importance of the reverse logistics can be judged from the fact that the average reverse logistics costs are 9.5% of total logistics costs (Daugherty *et al.*, 2001). The changing technology, decreasing product life cycle and liberal return policies are increasing the volume of returned products. In a study of US market, Rogers and Tibben-Lembke (1998) found that returns in reverse logistics are 50% for magazine publishers, 20–30% for book publishers, 18–35% for catalogue retailers and 10–12% for electronic distributors. Effective handling of reverse logistics transactions can result into economic and strategic benefits (Chanintrakul *et al.*, 2009; Vedpal and Jain, 2011). Many companies have realized that reverse logistics practices can be combined with source reduction processes to gain competitive advantage and at the same time can achieve sustainable development (Diabat and Kannan, 2011; Frota Neto *et al.*, 2008; Lee *et al.*, 2010; Seuring and Müller, 2008).

In many industries, original equipment manufacturers (OEMs) are looking for efficient ways to integrate reverse logistics into their supply chains to recover economic value from returned products and reduce disposal costs (Autry, 2005; Realff *et al.*, 2000). As OEMs have more knowledge on products and markets, they can operate the manufacturing and remanufacturing activities together and optimize the value of the closed-loop system. Remanufacturing of used products and bringing them back to the market provides not only the environmental and customer benefits but it also reduces the production cost of OEMs (Lee *et al.*, 2009). Compared with normal production, manufacturers can save about 40-60% of the cost while paying for only 20% of the manufacturing effort (Dowlatshahi, 2000). Kim *et al.* (2008) demonstrated that a remanufactured product uses less than 20% of the materials, 16% of the energy and releases only 35% of the greenhouse gas emissions of those released in the process of producing a new product.

Reverse logistics is mainly regulatory driven in Europe where governmental regulations are compelling businesses to address recovery and disposal of end-of-life products; profit driven in USA where value is recovered where ever possible; and in incipient stage in developing countries of the world including India (Srivastava and Srivastava, 2006). The implementation of reverse logistics is not an easy task in emerging countries like India because of the absence of societal pressure and insensitiveness to environmental issues, in addition to the price sensitive market. In India product returns are often regarded as a cost of doing business and are generally carried out by the unorganized sector for recyclable material such as paper, metals and glass, etc.

Most of the organizations are yet to realize the strategic potential of efficient closed-loop supply chain. But this scenario is changing for good, as there is more interest in CLSC now than ever before. To implement effective and efficient CLSC, organizations need to make strategic planning for: (i) the location and allocation of facility centers, and (ii) decision making at different stages of reverse logistics. So it is necessary to study the existing reverse logistics and closed-loop supply chain models, and develop a generalized closed-loop supply chain model which will help the organizations for easy implementation and decision making in reverse logistics and closed-loop supply chain.

1.5. Research Objective

The success of closed-loop supply chain relies on the operational profitability of the underlying supply chain. One of the fundamental issue in this context is to establish an effective and efficient infrastructure via optimal network design. This, in turn, entails identifying the roles of the existing and/or potential supply chain entities, as well as the interactions between these entities, to manage the physical flows associated with reverse logistics. An efficient network for closed-loop supply chain leads to a significant return on investment as well as reduction in environmental impact. The objectives of our study are:

(i) Design and Optimization of a generalized closed-loop supply chain

- To design a multi-product, multi-echelon capacitated closed-loop supply chain framework and single objective optimization model in an uncertain environment for single-time period returns, which will further be extended to multi-time period returns with inventory flow. A fuzzy mixed-integer linear programming model (MILP) will be developed to optimize the location and allocation of parts at each facility center, number of products to be remanufactured and number of parts to be purchased from external suppliers in order to maximize the profit of organization.
- To design and optimize a multi-objective closed-loop supply chain considering the uncertainty in parameters. The first objective will be to maximize the profit of organization and the second objective will be to minimize the environmental impact in terms of carbon footprints of the reverse transportation.

(ii) Development of multi-criteria decision models

Development of fuzzy multi-criteria decision making models for the assessment and evaluation of collection methods, product recovery processes and network configurations under the inherent uncertainty of reverse logistics.

1.6. Methodology

To accomplish the objectives of the study following tasks will be performed:

- A through literature review of the existing network and decision making models in reverse logistics and closed-loop supply chain.
- Design of a generalized closed-loop supply chain framework based on literature review and gap analysis.
- Mathematical modeling and optimization of the single objective closed-loop supply chain.
- Mathematical modeling and optimization of the multi-objective closed-loop supply chain.
- Development of multi-criteria decision model for the assessment and evaluation of collection methods in reverse logistics.
- Development of multi-criteria decision model for the assessment and evaluation of product recovery methods in reverse logistics.
- Development of multi-criteria decision model for the assessment and evaluation of network configurations in reverse logistics.
- A case study for the assessment and evaluation of lithium-ion battery recycling processes.

The following Table 1.2 shows the link between model/methodology proposed for each objective.

Table: 1.2 Model/methodology for each objective

Objectives	**Model/Methodology**
(i) Design and optimization of a generalized closed-loop supply chain • Single objective optimization • Multi-objective optimization	Fuzzy mixed-integer linear programming ϵ-constraint method
(ii) Development of multi-criteria decision models for the assessment and evaluation of: • collection methods, • product recovery processes and • network configurations	Integrated fuzzy analytical hierarchical process (Fuzzy AHP) and fuzzy technique for order preference by similarity to ideal solution (Fuzzy TOPSIS)

1.7. Significance of the Study

Significance of the study is that it will help the organizations for strategic decision making to implement reverse logistics. A generalized closed-loop supply chain framework and optimization model will be developed that considers the different costs (like incentive to customer, processing and set-up cost at facility centers, transportation cost, profit from recycling and waste disposal cost), different product recovery options (like reuse, recycle, refurbishing and disposal), and uncertainty in parameters (like demand of product, unit cost of collection, disassembly, refurbishing and disposal, set-up cost at each facility center, capacity of each facility center, unit purchasing cost and maximum percentage of parts that can be reused, refurbished recycled and disposed) simultaneously in the model. The developed model will help the organizations to calculate the optimal number of products to be remanufactured and the optimal number of parts to be purchased from external suppliers to maximize the profit of organization. It also provides the optimal location and allocation to different collection centers, disassembly centers, refurbishing centers and external suppliers.

Secondly the development of multi-criteria decision models for the assessment and evaluation of collection methods, product recovery methods and network configurations will help organizations in strategic decision making to prioritize and develop the collection, product recovery and network facilities accordingly. The study is also significant for researchers working in the field of reverse logistics and other similar terms as the study provides an exhaustive literature review and gap analysis of the existing network model in reverse logistics.

1.8. Outline of the Thesis

Chapter 1 introduces the topic of research and describes various parts of the research topic. Chapter 2 provides a review of the literature on network design and optimization models for reverse logistics and closed-loop supply chain. The research gaps are also identified in this chapter for proposing a research framework. Chapter 3 provides a multi-product, multi-echelon, capacitated closed-loop supply chain framework and a single objective optimization model considering uncertainty in parameters. A fuzzy mixed-integer linear programming model is proposed for single-time period return, which is further extended to multi-time period return to decide optimally the location and allocation of parts at each facility center, number of products to be remanufactured and number of parts to be purchased from external suppliers in order to maximize the profit of organization. Chapter 4 provides the design and optimization of a multi-objective closed-loop supply chain considering the economical and environmental factors with uncertainty in parameters. The carbon footprint of reverse transportation is considered as the environmental factor. The proposed network is modeled with fuzzy MILP and solved with ε-constraint method. Chapter 5, 6 and 7 provides an integrated fuzzy multi-criteria decision model for the assessment and evaluation of collection methods, product recovery processes and network configurations in reverse logistics respectively. Chapter 8 presents a case study for the assessment and evaluation of lithium-ion battery recycling processes in Germany. Finally, chapter 9 gives the conclusions of the research work along with limitations of the study and future scope of work.

CHAPTER 2

LITERATURE REVIEW

This chapter presents a thorough review of the literature on reverse logistics covering the definitions and scope of reverse logistics, brief history of reverse logistics, elements of reverse logistics and network design models in reverse logistics.

2.1. Reverse Logistics: Definitions and Scope

One of the earliest definitions of reverse logistics (RL) was given by Lambert and Stock in1981. They described it as “going the wrong way on a one-way street because the great majority of product shipments flow in one direction”(Lambert and Stock, 1981). This is similar to a definition by Murphy (1986), who defined reverse logistics as the “movement of goods from a consumer towards a producer in a channel of distribution.” Throughout the 1980s, the scope of reverse logistics was limited to the movement of material against the primary flow, i.e. from the customer toward the producer.

In the early 1990s, a formal definition of reverse logistics was put by the Council of Logistics Management (Stock, 1992), stressing the recovery aspects of reverse logistics as given in Table 2.1. The definition by Stock (1992) was broad and had its origin from a waste management standpoint. Further in 1998 three definitions were given to reverse logistics by Stock (1998), Carter and Ellram (1998) and Rogers and Tibben-Lembke (1998), as given in Table 2.1. The definition by Stock (1998) is focused on product recovery while the definition by Carter and Ellram (1998) is more focused for environmentally consciousness of the industries. While Rogers and Tibben-Lembke (1998) 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.” However, this definition is limited in scope as many products are returned to a point of recovery and not their origin. Therefore, De Brito and Dekker (2002), puts forward a broader perceptive of RL as, “the process of planning, implementing and controlling backward flows of raw materials, in-process inventory, packaging and finished goods, from a manufacturing, distribution or use point, to a point of recovery or point of proper disposal”. Here the expression “point of recovery” is used instead of “point of origin” as flows may go back to other points of recovery also. The reverse logistics association (2009) referred the term 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.” The recent definition given by Govindan *et al.*, (2015) has the explicit business point of view instead of other factors like legal, social responsibilities, or even operational and technical details, it will help the practitioners to focus on the profitability and value of their RL/CLSC instead of cost efficiencies or other costly objectives. The definitions or concept related to reverse logistics, as given by different authors is given in Table 2.1.

From Table 2.1 it is observed that earlier the scope of RL was limited to reverse flow of material for recycling or waste disposal (Stock, 1992). Further it was recognized that other than material recovery, reverse logistics can also provide value added recovery through various product recovery methods like reuse, remanufacturing, refurbishing, or cannibalizing (Rogers and Tibben-Lembke, 1999). Later with the increasing demand of sustainability researchers started considering environmental and social factors along with the economical factors, in the design of reverse logistics. In summary the scope of reverse logistics has changed with time, starting with a sense of reverse direction, going through product recovery and finally considering the environmental and social factors of sustainability, thus widening its scope.

Table 2.1: Definitions of reverse logistics related studies

References	**Definitions of reverse logistics**
Lambert and Stock (1981)	“going the wrong way on a one-way street because the great majority of product shipments flow in one direction”
Murphy (1986)	“…movement of goods from a consumer towards a producer in a channel of distribution.”
Stock (1992)	“...the term often used to refer to the role of logistics in recycling, waste disposal, and management of hazardous materials; a broader perspective includes all issues relating to logistics activities to be carried out in source reduction, recycling, substitution, reuse of materials and disposal.”
Thierry *et al.*(1995)	“.…the management of all used and discarded products, components and materials…under the responsibility of a manufacturing company”
Guide Jr and Srivastava (1997)	“…the strategies to increase product life consisting of repairing, remanufacturing and finally recycling products.”
Stock (1998)	“…the role of logistics in product returns, source reduction, recycling, materials substitution, reuse of materials, waste disposal, and refurbishing, repair, and remanufacturing”.
Carter and Ellram (1998)	“…the process whereby companies can become environmentally efficient through recycling, reusing, and reducing the amount of materials used.”
Rogers and Tibben-Lembke (1998)	“…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.”
Fleischmann (2001)	“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.”
Dowlatshahi (2000)	“…a supply chain that has been redesigned to manage the flow of products or parts destined for remanufacturing, repairing, or disposal and to effectively use the resources.”
De Brito and Dekker (2002)	“…the process of planning, implementing and controlling backward flows of raw materials, in-process inventory, packaging and finished goods, from a manufacturing, distribution or use point, to a point of recovery or point of proper disposal”
Hu *et al.*(2002)	“…the process of logistics management involved in planning, managing, and controlling the flow of wastes for either reuse or final disposal of wastes”.
Guide Jr *et al.* (2003)	“…supply chains that are designed to consider the processes required for returns of products, in addition to the traditional forward processes”
Guide *et al.*(2003a)	“…include traditional forward supply-chain activities and the additional activities of the reverse supply chain”
Savaskan *et al.* (2004)	…the distribution systems that use a combination of manufacturing and remanufacturing

Table 2.1 Definitions of reverse logistics related studies (contd.)

References	Definitions of reverse logistics
Serrato *et al.* (2007)	"…to include all activities associated with collecting, inspecting, reprocessing, redistributing, and disposing of items after they were originally sold."
Dowlatshahi (2009)	"….the process by which a manufacturing entity systematically takes back previously shipped products or parts from the point of-consumption for possible recycling, remanufacturing, or disposal."
Reverse Logistics Association (2009)	"…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"
Ye *et al.* (2013)	"…a series of activities necessary to retrieve a product from the point of consumption to either dispose of it or recover economic and environmental value."
Govindan *et al.* (2015)	"… closed-loop supply chain management is 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."

Since reverse logistics is relatively new research area, therefore some similar terms are encounter in the literature (De Brito, 2004). Kumar and Dao (2006) observed that different authors have used different terminologies to refer to the same concepts or the same terminologies to different concepts in the area of reverse supply chain management.

Reverse logistics is a commonly used term. It may have a narrow or broad scope. The narrow scope of reverse logistics refers to the actual movement and management of reverse flows of products/parts/materials from customers to suppliers (Tibben-Lembke and Rogers, 2002). The focus then is on logistics issues such as transportation modes and routing, pick-up scheduling, and the use of third-party logistics providers to optimize the logistics capability (Kumar and Dao, 2006). The broader scope of RL include activities that support the management of used products including picking them up, sorting them out, and reusing them in different ways (Dowlatshahi, 2000). Srivastava (2008) in his paper entitled 'network design for reverse logistics' considered collection, sorting-testing, product recovery and redistribution as the basic activities of reverse logistics.

Sasikumar *et al.*(2010), Lau and Wang (2009), Wadhwa *et al.* (2009) are few other researchers who have also considered the same key elements of the reverse logistics.

Reverse supply chain (RSC) refers to a series of activities necessary to retrieve a product from a customer for the product recovery or disposal (Guide Jr and Van Wassenhove, 2002; Prahinski and Kocabasoglu, 2006). Pochampally and Gupta (2003) considered the collection, recovery and demand as the key elements of RSC network design. Sasikumar and Kannan (2008) have considered collection, sorting, and product recovery as the key activities of RSC. Jia and Jian (2010) have also considered collection, testing, remanufacturing and redistribution as the key activities of RSC.

From the above discussion on the key elements/activities of reverse logistics and reverse supply chain, it is observed that the key elements/activities are same for the both and have been interchangeably used in the literature. The terms reverse logistics and reverse supply chain will be used interchangeably in this work meaning the effective and efficient management of the collection, sorting, testing and the recovery of returned products.

Further based on the network type the reverse supply chain can be of two types, i.e. open-loop supply chain and closed-loop supply chain. An open-loop supply chain has a ‘one-way’ structure in the sense that flows enter at one point and leave at another point (Fleischmann *et al.*, 2000). Recycling is often described as an open-loop system, because the products are not returned to the original manufacturer but can be reused in other industries. In recent years, simultaneous consideration of reverse and forward flows (i.e the closed-loop supply chain) has become more popular. The closed-loop supply chain (CLSC) is concerned with transforming the supply chain into a closed-loop by establishing an infrastructure to manage both the forward and reverse channels in a coordinated manner (Akçalı *et al.*, 2009). It has become an attractive alternative for optimizing end-of-life process activities of the products (Kongar and Gupta, 2006), because of the increasing pressure of legislations governing end-of-life products, imposing new minimum requirements related to recycling rates, recycled content and product take-back percentages.

Recentaly Govindan *et al.* (2015) has provided a comprehensive literature review of the reverse logistics/closed-loop supply chain covering 382 papers from year 2007-2013.

2.2. Brief History of Reverse Logistics

The idea of Reverse logistics (RL) has been around us for a long time, but the naming is difficult to trace with exactness (De Brito, 2004). According to Walden (2005), the history of reverse logistics find its root from the American Civil War (1861-1865). Overby (1992) mentioned that at the end of the American Civil War (1861-1865), General William T. Sherman realized that the nature of his armies campaign would be a matter of supply and mobility. The roots of today's retail returns issues lies in the customer service policy of Montgomery Ward's (Walden, 2005). Montgomery Ward's is an American furniture shop established since 1872; with the policy that if the customer is not 100% satisfied, they could bring it back for a full refund. Material shortages during World War II (1942) created a need to rebuild automobile parts and started a trend that continues until today (Walden, 2005).

The next major date of interest in reverse logistics is the 1984 Tylenol scare (Walden, 2005). Johnson & Johnson along with McNeil Laboratories quickly replaced the "tainted lot" of Tylenol by new lots with tamper proof bottles and set the new standard for reverse logistics. In 1991, The Federal Republic of Germany passed recycling ordinances in the environmental reverse flow. These ordinances include the provisions for fines and prosecution for violators of the ordinances, and stricter guidelines for the handling and transporting of hazardous materials (Walden, 2005). In 1996, the German ordinances led to a United Kingdom legislation that requires the shippers and manufacturers to be responsible for the return and recycling of packing materials (Walden, 2005). In 2001 European Union (EU) establishing a goal of 50-65% recovery or recycling of packaging waste with the implication for the rest of the world that they have to be compliant if they want to do business with the EU. The August 2003 edition of Jane’s Defense Weekly reported, “There is a 40 hectare area in Kuwait with items waiting to be retrograded to the US.” This is equivalent to approximately 150 Wal-Mart supercenters and an efficient reverse logistics system is required to process this (Walden, 2005).

The reuse of products or materials is not a new phenomenon (Fleischmann *et al.*, 1997), waste paper recycling, deposit systems for soft drink bottles, and metal scrap brokers are all examples that have been around for a long time. However, reverse logistics as a research field is relatively new. Research on reverse logistics has been growing since the early seventies, with the terms like reverse flow or reverse channel, but it was either related to waste management (Gilson, 1973; Zikmund and Stanton, 1971) or to recycling (Guiltinan and Nwokoye, 1974). The publication on strategies and modeling of reverse logistics came in 1980s.

2.3. Elements of Reverse Logistics

The three major elements of reverse logistics as discussed in literature are collection, inspection and sorting and product recovery. The detailed review of these elements of reverse logistics is provided below.

2.3.1 Collection

Collection is the first and an important element of the reverse logistics (Schwartz, 2000; Wojanowski *et al.*, 2007). It refers to all activities rendering used products availability and moving them physically to some point where further treatment is conducted for product recovery (Sasikumar and Kannan, 2008). It is to be noted that collection, to some extent, is imposed by legislation, e.g. Directive 94/62/EC for packaging material in Germany (Kapetanopoulou and Tagaras, 2011), white and brown goods in Netherland (Fleischmann *et al.*, 2000). According to Fleischmann *et al.* (2004), companies need to choose how to collect recoverable products from users, where to inspect collected products in order to recover valuable resources, where to reprocess collected products, and how to distribute recovered products to customers. Literature on collection in RL can be divided into three categories, i.e. location-allocation of collection centers, methods of collection and collection with incentive for product acquisition (Table 2.2).

Table 2.2: Literature on collection in reverse logistics

Collection activity	**References**
Location-allocation of collection centers	Kroon and Vrijens (1995); Jayaraman *et al.* (1999); Jayaraman *et al.*(2003); Realff *et al.* (2004); Beamon and Fernandes (2004); Listeş and Dekker (2005); Min *et al.*(2006a); Wang and Wen-Cheng (2007); Üster *et al.* (2007); Aras *et al.*(2008); Demirel and Gökçen (2008); Lee *et al.*(2010); Pishvaee *et al.*(2010); Pishvaee *et al.*(2011); Pishvaee and Razmi (2012); Kannan *et al.* (2012); Amin and Zhang (2013a); Özkır and Başlıgil (2013).
Methods of collection	Fleischmann *et al.*(2000), Krumwiede and Sheu (2002), Meade and Sarkis (2002), Murphy and Poist (2003), Savaskan *et al.* (2004), Serrato *et al.*(2007), Meade *et al.*(2007), Wojanowski *et al.*(2007), Ko and Evans (2007), Karakayali *et al.*(2007), Min and Ko (2008), Efendigil *et al.*(2008), Barker and Zabinsky (2008; 2011), Lambert *et al.*(2011).
Collection with incentive for product acquisition	Guide and Van Wassenhove (2001), Guide *et al.*(2003b), Choi *et al.* (2004), Ray *et al.*(2005), Yalabik *et al.* (2005), Wojanowski *et al.* (2007), Aras *et al.*(2008), Mitra and Webster (2008), Aksen *et al.*(2009), Liang *et al.* (2009).

Location-allocation of collection centers

Most of the literature in the field of collection in reverse logistics is related to location-allocation of collection centers (Table 2.2). Kroon and Vrijens (1995) studied the location-allocation of returnable containers to create a return logistics system. Spengler *et al.*(1997) developed a multi-stage, multi-product and a multi-level mixed-integer linear programming (MILP) model for location of warehouses in German steel recycling industry. Jayaraman *et al.* (2003) formulated a mixed integer programming (MIP) model to determine optimal number of collection and refurbishing centers and their location for hazardous products.

Min *et al.* (2006a) proposed a MILP model and a genetic algorithm to determine the location and allocation of collection centers and centralized return centers. Aras and Aksen (2008) formulated a mixed-integer nonlinear facility location-allocation model to determine both the optimal locations of the collection centers and the optimal incentive values for each return type so as tomaximize the profit fromthe returns. Mutha and Pokharel (2009) proposed a mathematical model for the design of an RL network handling product returns. Üster et al. (2007); Demirel and Gökçen (2008); Lee et al.(2010); Pishvaee et al.(2010); Pishvaee et al.(2011); Pishvaee and Razmi (2012); Kannan et al. (2012); Amin and Zhang (2013a); Özkır and Başlıgil (2013) are few of other authors which considered location-allocation of collection centers in their model.

Methods of collection

Literature suggests three methods of collection – collection by original equipment manufacturer (OEM), collection with retailers and collection with third party logistics providers. Lambert *et al.* (2011) proposed that responsibility of collection may rest either with the company or third party or the customers. Serrato *et al.* (2007) formulated and analyzed a Markov decision to evaluate outsourcing in reverse logistics. Meade and Sarkis (2002) proposed a conceptual model for selection and evaluation of the third party logistic providers. Diabat *et al.* (2013) analyzed the integrations among the barriers that may hinder the implementation of third party logistics using interpretive structural modeling. Some authors have proposed either combining retail activities with the collection of used products (Wojanowski *et al.*, 2007) or outsourcing of RL activities to thrid party logistics providers (Meade *et al.*, 2007; Murphy and Poist, 2003).

Savaskan *et al.* (2004) compared collection through third-party logistics providers, collection through retail outlets, and the collection through manufacturer's own channels. A product category in which there is no distinction between manufactured and remanufactured product is considered in the study. The paper concluded that collection through retailers is the best option and third party collection is the least preferred option because the payment made to third party for undertaking collection is a direct cost to supply chain that does not increase the final demand and therefore reduces the profitability of product remanufacturing.

de Figueiredo and Mayerle (2008) proposed an analytical model for designing collection networks where the manufacturer, defined as the recycler, was under the regulation of using a decided percentage of recovered products. The model considered incentives paid to the consumer or collection agents for returned items, number of collection centers and their location when designing collection networks for optimal collection costs. Aras and Aksen (2008) proposed a model to determine optimal location for establishing collection centers and to determine the incentive to be paid for returning the product. The returned products were categorized with different quality levels and the incentives were planned based on these quality levels. The return process requires the selection of the most appropriate collection channel (manufacturer, retailer, or third-party) and planning the reverse network flows (collection centers and routes) (Jayaraman *et al.*, 2003).

Barker and Zabinsky (2008; 2011) in their conceptual framework for decision making in reverse logistics network design categorized collection into two types - proprietary collection and industry-wide collection. Based on work of Barker and Zabinsky (2008), Table 2.3 provides two type of collection systems, i.e. industry-wide and proprietary collection systems. Both the categories have their own benefits and drawbacks. Industry-wide collection system is having the advantage of economies of scale and it does not complicate a company's forward supply chain. However, an individual company has limited control over this type of collection system. Proprietary collection system is particularly beneficial when the company has a strong direct relationship with its customer such as a lease-return relationship, or when there is high customer trade-in behavior. However, transportation costs may be higher, because a company-specific system cannot take advantage of economies of scale (Barker and Zabinsky, 2011).

Table 2.3: A review of the case studies based on collection system

Collection Type	**Reference**	**Case Study**
Industry-wide collection	Barros *et al.*(1998)	Construction sand recycling
	Chang and Wei (2000)	Municipal curbside waste
	Farrow *et al.* (2000)	Recycled plastic kayaks
	Guide and Van Wassenhove (2001)	Cellular phone remanufacturing
	Krikke *et al.* (1999a)	PC monitor recycling
	Louwers *et al.*(1999)	Carpet recycling
	Realff *et al.* (1999)	Carpet recycling
	Nagel and Meyer (1999)	Refrigerator remanufacturing
	Spengler *et al.*(1997)	Steel by-products
	Staikos and Rahimifard (2007)	Shoe recycling
	Wang *et al.* (1995)	Cardboard recycling
	Kleineidam *et al.*(2000)	Paper recycling
	Hong *et al.* (2006a)	e-Scrap recycling
Proprietary collection	Bartel (1995)	Printer toner cartridge recycling
	Fleischmann *et al.*(2000)	Business computer refurbishing
	Yender (1998)	Battery recycling
	Duhaime *et al.*(2001)	Reusable postal containers
	Gupta and Chakraborty (1984)	Glass scrap recycling
	Krikke *et al.* (1999b)	Copier refurbishing
	Rudi *et al.* (2000)	Wheelchair refurbishing
	Kroon and Vrijens (1995)	Reusable packaging
	Thierry *et al.* (1995)	Copier refurbishing

Source: adapted and modified from Barker and Zabinsky (2008)

Collection with incentive for product acquisition

Product acquisition is a crucial step in reverse logistics because consumers do not typically have any motivation to return products (Guide *et al.*, 2003b). The acquisition of cores is a complex set of activities that requires careful coordination to avoid the uncontrolled accumulation of its inventory, or unacceptable level of customer service (Daniel *et al.*, 2000). The logical planning should set collection options that provide consumers with hassle free return and the motivation to return products by offering reasonable incentives on the return of used products (Guide Jr, 2000). The need to encourage and manage used product acquisition via incentive mechanisms is also recognized by Guide and Van Wassenhove (2001). They showed that it is possible for the firms to control the quality of returned products by offering financial incentives. They proposed two primary systems for obtaining used products from the end-users - the waste stream system and the market-driven system. In the waste stream system, firms passively accept all retuned products from the waste stream. It relies on diverting discarded products from landfills by making producers responsible for the collection and reuse of their products. In waste stream system firms are unable to control the quality of returns and therefore consider the large volumes of returns a nuisance, and naturally tend to focus on the development of low cost reverse logistics networks. In the waste stream system cost reduction is encouraged and the fundamental issue is to minimize the amount of money the firm loses. In a market-driven system, end-users are motivated to return end-of-life products by financial incentives such as deposit systems, credit toward a new unit, or cash paid for a specified level of quality (Guide and Van Wassenhove, 2001). In this system firms are able to control the level of quality of returned products since acceptance of returns is conditioned by standards. A combination of the market-driven and waste stream approaches is also possible.

Guide *et al.*(2003b) and Ray *et al.*(2005) presented the analytical models for the relation between financial incentives and used product acquisition. Guide *et al.*(2003b) developed a model to determine the optimal product acquisition price for used products of varying quality and the optimal selling price for remanufactured products to increase the profitability of remanufacturing. Ray *et al.*(2005) examined the situation where a firm offers trade-in-rebates to its customers in an effort to hasten their replacement decisions, and to determine optimal selling prices of new products and optimal trade-in-rebates. Aras *et al.* (2008) suggested offering attractive incentives to motivate the end user to return the product to a designated place. They formulated a mixed-integer nonlinear facility location-allocation model to find both the optimal locations of a predetermined number of collection centers and the optimal incentive values for different return types. It is also concluded that uniform incentive policy is inferior to quality based incentive when the proportion of low quality is relatively high (Aras *et al.*, 2008).

Aksen *et al.*(2009) presented bi-level programming models describing the subsidization agreement between the government and a company engaged in collection and recovery operations. Mitra and Webster (2008) examined the effect of government subsidy on the profit of a remanufacturer when subsidy is proportional to the remanufacturing volume. Wojanowski *et al.* (2007) developed a model to determine the optimal sales price by charging a refundable deposit to ensure product returns. Bulmuş *et al.* (2014) considered an OEM that decides on the acquisition prices offered for returns from different quality types and on selling prices of new and remanufactured products, in single period setting. They developed a procedure for determining the optimal prices and corresponding profit of the OEM, and conduct a sensitivity analysis to understand the effect of different model parameters on the optimal strategies and profit. Choi *et al.* (2004) and Yalabik *et al.* (2005) also conducted the similar studies for calculating the optimal acquisition price.

Wei *et al.* (2015) aims to explore how the manufacturer and the retailer make their own decisions about wholesale price, retail price, and collection rate under symmetric and asymmetric information conditions.

From the above review it is observed that collection in an important activity in reverse logistics but is a complex and costly activity, particularly when the customers do not have any motivation to return. Collection activities are either initiated by legislation or are profit driven. Most of the research on collection in reverse logistics is either on the location and allocation of collection facilities (Amin and Zhang, 2013a; Kannan *et al.*, 2012; Pishvaee and Razmi, 2012) or to determine the optimal sales price or the incentive for core acquisition (Bulmuş *et al.*, 2014; Choi *et al.*, 2004; Guide *et al.*, 2003b; Wojanowski *et al.*, 2007; Yalabik *et al.*, 2005).

2.3.2 Inspection and sorting

The products are inspected and sorted after collection. Inspection and sorting consists of operations that determine whether a given product is reusable or not, and if yes, then to what extent. Inspection and sorting results in splitting the flow of used products according to distinct reuse or disposal options, e.g. distinguishing repairable and recyclable subassemblies of copiers (Krikke *et al.*, 1999b).

Barker and Zabinsky (2008) identified that sorting/testing can either be done at centralized location or decentralized location and discussed the trade-offs considerations. Owing to efficiencies from higher volumes, a centralized site is common for a commodity-type product, such as construction sand recycling (Barros *et al.*, 1998) or carpet recycling (Louwers *et al.*, 1999). A centralized site is desirable for high-cost testing procedures as it minimizes the cost of testing equipments and specialized labor. One drawback of centralized sorting and testing is that in this system the waste will be identified after its transportation to the testing facility therefore transportation cost will be higher. Distributed sort/test sites are often used if low cost testing procedures are available, such as for paper recycling (Bloemhof-Ruwaard *et al.*, 1996), machine refurbishing (Thierry *et al.*, 1995), or reusable containers and equipment (Kroon and Vrijens, 1995). In this system scrap is identified early and shipped to waste disposal center, thus reduces the transportation costs. However, testing procedures must be consistent and reliable at all centers. The network may be more complicated because scrap and usable return product are shipped in separate streams. Srivastava and Srivastava (2006) also discussed that inspection/sorting may be carried out either at the point/time of collection or afterwards (i.e. at rework facilities). Inspection/separation may encompass disassembly, shredding, testing, sorting, and storage (Fleischmann *et al.*, 1997).

Disassembly is a systematic method of separating a product into its constituent parts, components, subassemblies or other groupings and it is also used to remove the toxic elements. It may involve dismantling, demolition or reprocessing (Sasikumar and Kannan, 2008). Most of the literature in disassembly is related to find out the degree of disassembly or to improve the efficiency of disassembly. Brennan *et al.* (1994) discussed the operational planning issues in assembly/disassembly environment. de Ron and Penev (1995) proposed an approach to determine the degree of disassembly at a single point of time. Penev and de Ron (1996) presented models to decide the disassembly sequence and routing, which aims at minimizing the operational costs while fulfilling the production due date. Lambert (1997) presented a graph-based method for determining the optimum sequence for selective disassembly of discarded complex products. Taleb *et al.* (1997) considered the disassembly scheduling problem for complex product structures with parts and materials commonality. Mok *et al.* (1997) described the use of information and technologies to improve the processes of disassembly. Gungor and Gupta (1997) proposed heuristic approaches for disassembly planning for the optimization of recycling processes. Johnson and Wang (1998) presented a systematic procedure for generating an optimal disassembly sequence based on maximizing the profits of material recovery taking into account material compatibility, clustering for disposal and concurrent disassembly operations. Veerakamolmal and Gupta (1999) discussed a technique for analyzing the design efficiency of electronic products in order to study the effect of EOL disassembly and disposal on the environment. Viswanathan and Allada (1999) and Tang *et al.* (2001) proposed the group technology to improve the efficiency of disassembly by taking into account the similarities in the operations to be carried out on each product.

Kuo *et al.* (2000) presented a graph-based, heuristic approach to perform disassembly analysis for electromechanical products. Pan and Zeid (2001) considered several examples of disassembling products such as a lamp, a car, a window fan, and a two stroke engine. Gungor and Gupta (2001) proposed a branch and bound algorithm for obtaining approximate optimal disassembly sequences. Tiwari *et al.*(2002) presented a cost-based heuristic analysis for a circuit board disassembly in which various components of a product and their assembly relationships are represented by a Petri Net diagram. Veerakamolmal and Gupta (2002) applied learning algorithms for the disassembly of electronic devices. Torres *et al.* (2004) described the process of obtaining a non-destructive automatic disassembly system for personal computers. Inderfurth and Langella (2006) addressed the disassemble-to-order problem by using heuristic techniques, where the yields of disassembly were stochastic. Tang *et al.*(2004) presented a model for the economic evaluation of the disassembly processes. Andrés *et al.* (2007) proposed a two-phase approach using meta-heuristics for determining the optimal disassembly sequence when the disassembly system has a cellular configuration.

From the above review it is determined that inspection and sorting can either be done at centralized location or decentralized location (Barker and Zabinsky, 2008); or may be carried out either at the point/time of collection or afterwards at rework facilities (Srivastava and Srivastava, 2006). Each of the procedure has its own trade-off advantages and disadvantages.

2.3.3 Product recovery

Product recovery is an important activity of reverse logistics to manage the flow of products or parts destined for remanufacturing, repairing, or disposal and to effectively use the resources (Dowlatshahi, 2000). Product recovery management includes strategies to increase the product's life by repairing and remanufacturing (Guide Jr and Srivastava, 1997). It involves diverting used products from the waste stream and seizing their remaining value (Guide and Van Wassenhove, 2001). This reduces the use of virgin natural resources, mitigates environmental pollution and eases the burden on limited landfill space (Wojanowski *et al.*, 2007). Many authors pointed out the importance of product recovery as an environmentally and economically sound way to achieve many of the goals of sustainable development (Ayres *et al.*, 1997; Ferrer, 1997a; Ferrer, 1997b; Kim *et al.*, 2008; Thierry *et al.*, 1995). Product recovery is generally carried out to recover hidden economical value, to meet market requirements or to meet Government regulations (Sasikumar and Kannan, 2008).

Sometimes resource recovery is not economically viable for the industry. In such cases, governments can resort to a wide range of policy tools to facilitate achievement of their targets. Mandatory take-back legislation, such as Germany's packaging recycling law implemented via the well-known Green Dot program, constitutes the most radical approach but typically difficult to enforce. Price-based policies constitute a less challenging option in terms of implementation and monitoring. Examples of such policies include taxes on the use of virgin materials, recycling subsidies, disposal fees and deposit-refund requirements (Fullerton and Wu, 1998). Economics literature provides evidence that deposit-refund is the most preferable policy (Wojanowski *et al.*, 2007). A deposit-refund system requires consumers to pay a certain deposit at the time of purchase, which is refunded upon the return of the used product. Such systems have been commonly used in promoting return and reuse of product packages and containers, e.g. aluminum cans, glass bottles, car batteries, tires, etc.

Fleischmann *et al.* (2000) identified the common characteristics of product recovery networks and classified it into three types – bulk recycling networks, assembly product remanufacturing networks, and reusable item networks. Trade-off choices were discussed such as centralization versus decentralization of recovery activities, single-activity facilities versus multiple-activity facilities, and integrated network routing versus separate network routing. Some authors (Krikke *et al.*, 2008; Mukhopadhyay and Setoputro, 2005) advocates the use of modular product structure for improved recovery and optimal reuse of products as well as to obtain economic and higher ecological advantage. Veerakamolmal and Gupta (1999) proposed a technique to measure the design for disassembly index to analyze the design efficiency of modular electronic products.

Lund (1998) identified 75 separate product types that are routinely remanufactured, and developed criteria for remanufacturability. Industries that typically apply remanufacturing include automobiles, electronics and tyres. Guide *et al.* (2003b) considered the case of a cellular phone remanufacturing company that acquired used phones with different quality levels, remanufactured them to a single quality level and sold them. The objective was to determine the optimal acquisition prices for used phones and the selling price for remanufactured phones in order to maximize the profit. Van der Laan and Salomon (1997) proposed a hybrid manufacturing/remanufacturing system with stocking points for serviceable and remanufacturable products. Ferrer (1997a) examined the case of re-treading in the tyre remanufacturing process. Ferrer (1997b) addressed the complexity of PC remanufacturing and the difficulties in developing adequate recovery processes. Ferrer and Ayres (2000) studied the impact of remanufacturing to the economy. Sundin and Bras (2005) provided arguments for why used products should be remanufactured. Kerr and Ryan (2001) studied the Xerox photocopiers in Australia and attempted to quantify the life cycle environmental benefits achieved by incorporating remanufacturing into a product system.

Once a product has been returned to an organization, it has many recovery options. Jayaraman (2006) has identified seven recovery options as reuse, repair, refurbish, remanufacturing, retrieval, recycle and disposal. The first option is to sell the product as a used product if it meets sufficient quality levels. The second option is to clean and repair the product to working order. Product repair involves fixing and replacement of failed parts. Repair operations can be performed at the customer’s location or at a manufacturer controlled repair centre. The third option is to sell the product as a refurbished unit. In this the product does not lose its identity and is brought back to a specified quality level. Sometimes, refurbishing is combined with technology upgrading by replacing outdated modules and parts with technologically superior ones. The fourth option is to remanufacture. In this option the product will enter the reverse channel at the fabrication stage where it would be disassembled, remanufactured, and reassembled to flow back through the retail outlet back to the consumer as a remanufactured product. The purpose of remanufacturing is to bring the used products up to quality standards that are as rigorous as those for new products. The fifth option is to retrieve one or more valuable parts from the product. The sixth option is to recycle. In this option the product will most likely enter the reverse value channel in the raw material procurement stage where it may be reutilized with other raw materials to produce the virgin materials after some initial processing. In recycling, the identity and functionality of products and components is lost. The main purpose of recycling is to recover materials from used components and products. The seventh option is to recover the energy in the product through incineration. If the product is of no use even after re-processing the last option is waste disposal. The different product recovery options can be grouped into following three categories:

Direct recovery

It includes the items that can be reused directly after cleaning and minor maintenance. Reusable packages such as bottles (Torres *et al.*, 2004), pallets or containers (Kroon and Vrijens, 1995), telecommunications equipment (Linton and Johnston, 2000) are some of the examples of direct recovery. Re-use and re-sale are two options used under direct recovery. Re-use is a situation in which the product is used again, but there is no purchase, e.g. containers. Re-sale applies to situations where the products are sold again.

Process recovery

Different authors have categorized and classified the product recovery process. Thierry *et al.* (1995) considered repair, refurbish, remanufacture, cannibalize, and recycle as the five alternative product recovery options; Lambert *et al.* (2011) considered repair, reuse, remanufacture, upgrade, repackage, recycle, reconfigure, and revaluation as the recovery process alternatives; Johnson and Wang (1995) defined product recovery as a combination of remanufacture, reuse, and recycle; Sasikumar and Kannan (2008) divided product recovery process into direct reuse, recycling, remanufacturing, and repair; Skinner *et al.* (2008) mentioned destroying, recycling, refurbishing, remanufacturing, and repackaging of returned products as the five most widely used disposition strategies. Summary of the various alternative product recovery processes considered by some authors is shown in Table 2.4.

Table 2.4: Alternative product recovery processes

Citation	**Alternative Product Recovery Processes**
Thierry *et al.*(1995)	Repair, refurbish, remanufacture, cannibalize and recycle
Johnson and Wang (1995)	Combination of remanufacture, reuse, and recycle
Rose and Ishii (1999)	Reuse, service, remanufacture, recycle and disposal
Guide *et al.*(2000)	Repair, remanufacturing and recycling
Ferguson and Browne (2001)	Reuse, remanufacture and recycle
Lee *et al.* (2001)	Reuse, remanufacture, recycle, landfill, and incineration
King *et al.* (2006)	Repair, recondition, remanufacture, and recycle
Sasikumar and Kannan (2008)	Direct reuse, recycling, remanufacturing, and repair
Skinner *et al.* (2008)	Destroying, recycling, refurbishing, remanufacturing, and repackaging
Srivastava (2008)	Repair & refurbish, remanufacturing, and secondary market
Lambert *et al.*(2011)	Repair, reuse, remanufacture, upgrade, repackage, recycle, reconfigure, and revaluation

Toensmeier (1992), Thierry *et al.* (1995), King *et al.*(2006), Parkinson and Thompson (2003) and McConocha and Speh (1991) are few of the paper which provides the definitions of these product processes. Different product recovery processes have been compared based on value added recovery, degree of disassembly, operating cost, energy consumption (Lee *et al.*, 2001; Srivastava, 2008; Stahel, 1994; Wadhwa *et al.*, 2009).

Remanufacturing is an environmentally and economically sound way to achieve many of the goals of sustainable development. It closes the material use cycle and forms an essentially closed-loop manufacturing system. The aim of remanufacturing is to bring the product into ‘as new’ conditions by carrying out the necessary disassembly, overhaul, and replacement operations to get value-added recovery, rather than just materials recovery. Lund (1983) defined remanufacturing as ‘‘an industrial process in which worn-out products are restored to like-new condition. Through a series of industrial processes in a factory environment, a discarded product is completely disassembled. Useable parts are cleaned, refurbished, and put into inventory. Then the new product is reassembled from the old and, where necessary, new parts to produce a fully equivalent and sometimes superior-in performance and expected lifetime to the original new product.’’

Waste disposal

Disposal is required for products that cannot be reused for technical or economical reasons. This applies to products that are rejected at the separation level due to excessive repair requirements or to products that do not satisfy the market demand/potential, e.g. due to outdating. Disposal may include land-fill or incineration.

Product recovery is an important activity for the economical and environmental sustainability. It is either carried out for the economic profitability or to fulfill the legislation requirements. Literature has suggested different methods of product recovery like direct recovery (i.e. reuse and resale), process recovery (repair, refurbish, remanufacture, cannibalize etc.) and waste disposal (i.e. land-fill or incineration). A comparison of these product recovery processes and factors affecting its selection is given in chapter 6 (Assessment of product recovery processes).

2.4. Reverse Logistics Network Design Models

There exists a large literature on network design of traditional or forward supply chain management. However, the literature on network design for reverse logistics is limited. The literature on network design of reverse logistics can be classified according to type of framework, number of objectives, product recovery options, different costs, binary decision variables, and methods of handling uncertainty.

2.4.1. Based on type of framework

Based on the type of framework the reverse logistics models can be categorized into open-loop supply chain models and closed-loop supply chain models.

Open-loop supply chain (OLSC) models

An open-loop supply chain network is concerned with establishing an infrastructure to manage the reverse channel only i.e., the reverse activities and reverse flows. It has a 'one-way' structure, that flows enter at one point and leave at another point (Fleischmann *et al.*, 2000).

Recycling is often considered as an open-loop system. Barros *et al.* (1998) presented a case study addressing the design of a logistics network for recycling of construction sand in The Netherlands, to determine the optimal number, capacities, and locations of the depots and cleaning facilities. The authors proposed a multi-level capacitated facility location model as a mixed integer linear programming (MILP) problem which was solved via iterative rounding of LP-relaxations.

Spengler *et al.*(1997) developed a multi-stage, multi-product and multi-level MILP model for location of warehouse for the German steel recycling industry. The objective of the model was to determine which location to open and the amount of flow between the sources and sinks. A sink can be either a reuse or a disposal location. Facilities can be installed at a set of potential locations with different capacity levels and the corresponding fixed and variable processing costs. The maximum capacity of facility centers is restricted and the transportation cost between locations is linear. The amounts of waste generated at the sources are fixed, while the demand at the sinks is flexible within a range.

Louwers *et al.*(1999) proposed a continuous location model for the recycling network design of carpet waste. The objective of the study was to determine appropriate locations and capacities for the regional recovery centers taking into account the investment cost, processing cost and transportation cost. Realff *et al.* (1999) proposed a multi-level capacitated facility location MILP model for the carpet recycling in USA to determine the optimal number and location of collection sites and processing plants.

Pochampally and Gupta (2003) utilized a three-phase mathematical programming approach to effectively design an efficient reverse supply chain network. Phase I selects the most economical product from a set of used products, using a mixed-integer mathematical programming model, phase II implements the analytic hierarchy process to identify potential facilities in a set of candidate recovery facilities and phase III solves a single time-period discrete location model to achieve transportation of the right mix and quantities of goods across the reverse supply chain network.

Jayaraman *et al.* (2003) formulated an MIP model to determine an efficient strategy for the RL operations of hazardous products. The objective of the model was to find the optimal number and location of collection and refurbishing facilities with the corresponding flows of the hazardous products to minimize the total cost. Listeş and Dekker (2005) presented a stochastic programming approach by which a deterministic location model for product recovery network design may be extended to explicitly account for the uncertainties, with a case study on sand recycling in the Netherlands.

Pati *et al.* (2006a; 2006b) proposed a linear programming optimization model to minimize the supply chain cost for the Indian paper industry with wood and waste paper as two different sources of raw materials. Min *et al.* (2006a) proposed a MILP model and a genetic algorithm to solve the RL problem involving product returns. The objective of the model was to determine the location and allocation of collection centers and centralized return centers to minimize the hassles of customer associated with product return while minimizing the total cost.

Sharma *et al.* (2007) developed an MILP model to facilitate better leasing and logistics decisions (including end-of-life disposal options) from the perspective of an electronic equipment leasing company. Kara *et al.* (2007) presented a simulation model of an RL network for collecting end-of-life appliances in the Sydney metropolitan area and calculated the collection cost. Salema *et al.* (2007) proposed a capacitated, multi-product RL network considering the uncertainty in product demand and return. Lieckens and Vandaele (2007) presented a single product single level network model to determine which facilities should be operated at which capacity level and how the flow should be assigned so that the overall expected profit of the system is maximized taking into account the stochastic lead time. They also considered the penalty cost for not satisfying the demand of reuse customers and for not collecting the returns from disposer customers.

Pochampally and Gupta (2008) proposed a multi-phase fuzzy logic approach for the strategic planning of a reverse supply chain network to (i) select the most economical product using fuzzy cost benefit function, (ii) select the potential facility with analytical hierarchy process and (iii) minimize the overall cost using LINGO optimization tool. Min and Ko (2008) proposed an mixed integer programming (MIP) model and a genetic algorithm that can solve the reverse logistics problem involving the location and allocation of repair facilities for third party logistics. The objective of the model was to find the optimal location, number, and size of repair facilities/warehouses in the reverse logistics network under capacity limits and service requirements. Srivastava (2008) after conducting the informal interview with 84 stakeholders formulated a multi-echelon, multi-product, multi period MILP model as a bi-level optimization problem. The first optimization model decides the collection center opening decision and the second model determines the location and capacity addition decision for rework sites. Pati *et al.* (2008) formulated a mixed integer goal programming model to assist in proper management of the paper recycling logistics system in India and studied the inter-relationship among multiple objectives (with changing priorities) of a recycled paper distribution network. The proposed model also assists in determining the facility location, route and flow of different varieties of recyclable waste paper in multi-item, multi-echelon and multi-facility decision-making framework. Aras and Aksen (2008) addressed the problem of locating collection centers of a company for distance and incentive-dependent returns. They formulated a mixed integer non-linear facility location-allocation model to determine both the optimal locations of the collection centers and the optimal incentive values for each return type to maximize the profit from the returns. Frota Neto *et al.* (2008) developed a framework for the design and evaluation of sustainable logistic networks, in which profitability and environmental impacts are balanced. They introduced a new methodology based on the properties shared by multi-objective programming and data envelopment analysis.

Mutha and Pokharel (2009) presented a mathematical model considering the modular product structure with different disposal and recycling fractions for each module. The focus was on deciding the number of facilities with location and allocation of used module at an optimal cost. This model assumed only deterministic demands by assuming historical averages although the demands for remanufactured products could vary.

Closed-loop supply chain (CLSC) models

The configuration of the reverse logistics network has a strong influence on the forward logistics network and vice versa. Separating the design may result in sub-optimality; therefore the design of the forward and reverse logistics network should be integrated (Lee and Dong, 2008). The CLSC network design is concerned with transforming the supply chain into a closed-loop by establishing an infrastructure to manage both the forward and reverse channels in a coordinated manner (Akçalı *et al.*, 2009). In CLSC sources and sinks coincide so that flow cycles in the network (Fleischmann *et al.*, 2000).

Guide and Wassenhove (2009) defined CLSC 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. They identified five phases of CLSC – the golden age of remanufacturing as a technical problem (phase 1), from remanufacturing to valuing the RL process (phase 2), coordinating the reverse supply chain (phase 3), closing the loop (phase 4), and prices and markets (phase 5).

Kroon and Vrijens (1995) proposed a MILP model to design a closed-loop logistics system for reusable plastic containers. The objective of the model was to determine the number of containers required to run the system, an appropriate fee per shipment and location for the depots. At depots, containers are stored and maintained, shipped to a sender upon request, and eventually collected from the recipient. The expected volume and geographical distribution of demand is estimated on the basis of historical data.

Del Castillo and Cochran (1996) presented a pair of linear program and a simulation model to maximize the number of reusable containers. They modeled the reusable bottle production and distribution activities of a large soft drink manufacturer located in Mexico. However, transportation issues related to reverse logistics were not considered.

Jayaraman *et al.* (1999) analyzed the logistics network of an electronic equipment remanufacturing company in the USA. They presented a multi-product capacitated warehouse location MILP model for different supply and demand scenarios. The company's activities included collection of cores from customers, remanufacturing of collected cores, and distribution of remanufactured products. The optimal number and locations of remanufacturing facilities and the number of cores collected were determined considering investment, transportation, processing, and storage costs. Krikke *et al.* (1999b) presented an MILP model for a multi-echelon RL network design for copiers in the Netherlands. The MILP model is solved to minimize the operational costs and compare it with three pre-selected managerial solutions by fixing the locations.

Fleischmann *et al.* (2001) developed a generic integer programming formulation considering the integration of forward and reverse distribution. The impact of product return flows on logistics networks was analyzed. They took the case of photocopier remanufacturing and paper recycling, and showed the potential for cost savings with an integrated view rather than a sequential design of the forward and reverse distribution networks. Similarly, Fleischmann *et al.* (2003) considered the integration of CLSC and spare parts management at IBM. The proposed simulation model showed that procurement cost savings largely outweigh reverse logistics costs.

Schultmann *et al.* (2003) developed a hybrid approach with capacitated two level facility location model and flow-sheet simulation for spent batteries in the steelmaking industry and model was solved with GAMS. Krikke *et al.* (2003) developed a quantitative modeling approach to support decision-making concerning both the design structure of a product and the design structure of the logistics network. The model was handled using the real life R&D data of a Japanese consumer electronics company. Table 2.5 provides a literature review of the open-loop and closed-loop network design models.

Table 2.5: Literature on open-loop and closed-loop supply chain models

Framework Type	Citation
Open-loop Supply Chain Models	Barros *et al.*(1998), Louwers *et al.*(1999), Krikke *et al.*(1999b), Shih (2001), Jayaraman *et al.*(2003), Realff *et al.* (2004), Listeş and Dekker (2005), Amini *et al.*(2005), Min *et al.*(2006a), Lieckens and Vandaele (2007), Wang and Wen-Cheng (2007), Pati *et al.*(2008), Harraz and Galal (2011), Pishvaee and Razmi (2012), etc.
Closed-loop Supply Chain Models	Fleischmann *et al.*(2001), Kim *et al.*(2006), Salema *et al.*(2005), Salema *et al.*(2007), Beamon and Fernandes (2004), Ko and Evans (2007), Lu and Bostel (2007), Zhou *et al.*(2005), Lee *et al.*(2007b), Lee and Dong (2008), Kannan *et al.*(2008), Lee *et al.*(2007c), Mutha and Pokharel (2009), Dehghanian and Mansour (2009), Easwaran and Üster (2010), Lee *et al.*(2010), Özceylan and Paksoy (2012a), Amin and Zhang (2012), Amin and Zhang (2013a), Özceylan and Paksoy (2012b), Wang and Huang (2012), Özkır and Başlıgil (2013),(Amin and Zhang, 2013b) etc.

2.4.2. Based on number of objectives

Based on the number of objective the reverse logistics models can be categorized into single objective and multi-objective models.

Single objective models

Design and optimization of single objective models involves the optimization of a single objective function, e.g. the maximization of profit or minimization of total cost subject to some constraints. Table 2.6 provides a literature review of single objective models, based on framework type (i.e. closed-loop/open-loop), model/methodology, single product/ multi-product, single-time period/multi-time period and capacitated facility/un-capacitated facility planning.

Beamon and Fernandes (2004) developed a deterministic, static, multi-period integer programming model to study a CLSC in which manufacturers produce new products as well as remanufacture the used products. Sensitivity analysis was performed with respect to percentage of return in good quality, time horizon and interest rate. Dyckhoff *et al.*(2004) dealt with the expansion of a supply chain to closed-loop management. They presented a double layer closed-loop model and analyzed the material flow in an automotive cycle.

Min *et al.* (2005) developed a Lagrangian relaxation heuristic for solving the multi-echelon, multi-commodity, close-loop supply chain network design. However, the model did not consider temporal consolidation issues in a multiple planning horizon. French and LaForge (2006) conducted an empirical study of process industry to investigate re-use issues and practices related to CLSC from the producer’s perspective with the objective of identifying important issues in the field. They identified that process industry firms are quite diverse and the common beliefs about re-use in process industry firms do not apply to all process. Jayaraman (2006) presented an analytical approach named RAPP (Remanufacturing Aggregate Production Planning), for production planning and control of closed-loop supply chain with product recovery and reuse. The model was designed to aid operational decision-makers in an intermediate to long-range planning environment. Key decisions include the number of units of core with a nominal quality level that are disassembled, disposed, remanufactured and acquired in a given time period to minimize the total cost.

Min *et al.* (2006b) proposed a mixed integer non-linear programming model and genetic algorithm to minimize the total RL cost for the CLSC network involving both spatial and temporal consolidation of returned products at collection center. The key issues addressed in this study are: how many collection points to be established; where to locate the collection points; and how to direct customers to nearby collection points.

Table 2.6: Literature on single objective models based on type of framework, model/methodology, number of products, time period, and capacity of facility centers

Reference	**Type of Framework**	**Model / Methodology**	**Product**		**Time Period**		**Capacity**		**Objective**
			SP	**MP**	**ST**	**MT**	**UC**	**CP**	
Kroon and Vrijens (1995)	CLSC	MIP		√	√		√		To minimize the total cost by determining the optimal number of containers; the appropriate number of container depots and their locations, and the appropriate service, distribution and collection fees.
Barros *et al.*(1998)	OLSC	MILP/Linear relaxation		√	√			√	To minimize the total logistics cost by determining the optimal number, capacities, and locations of the depots and cleaning facilities for the recycling of sand from construction waste.
Louwers *et al.*(1999)	OLSC	Non-linear programming		√	√			√	To determine the location and size of regional recycling centers in Europe for a carpet waste management network taking into account the investment, processing and transportation cost.
Krikke *et al.*(1999b)	OLSC	MILP	√		√			√	To minimize the total cost by determining the optimal location of reprocessing facilities for a copier manufacturers.
Krikke *et al.* (1999b)	CLSC	MILP	√		√		√		To minimize the total cost by determining the optimal number and location of container depots; number of containers; and the appropriate service, distribution and collection costs.
Jayaraman *et al.*(1999)	CLSC	MILP		√	√			√	To minimize the total cost by determining the optimal location of remanufacturing/distribution facilities and to find the optimum quantities of transshipment, production and stock of cores and remanufactured products.
Shih (2001)	OLSC	MIP		√	√			√	To minimize the total cost by designing a reverse logistics system for recycling computers and home appliances in Taiwan.

SP: Single Product; MP: Multi-Product; ST: Single Time; MT: Multi-Time; CP: Capacitated; UC: Un-capacitated

Table 2.6: Literature on single objective models based on type of framework, model/methodology, number of products, time period, and capacity of facility centers (contd.)

Reference	**Type of Framework**	**Model / Methodology**	**Product**		**Time Period**		**Capacity**		**Objective**
			SP	**MP**	**ST**	**MT**	**UC**	**CP**	
Fleischmann *et al.*(2001)	CLSC	MILP	√		√		√		To minimize the cost by determining the location of plant, warehouse and disassembly center.
Jayaraman *et al.*(2003)	OLSC	MIP/ Heuristics	√		√			√	To minimize the total cost by determining the optimum location and allocation of collection and refurbishing sites.
Realff *et al.* (2004)	OLSC	MILP/Robust programming		√		√		√	To maximize the total profit by determining the optimal location of sites, capacity of sites and mode of transportation that connect the sites for carpet recycling in U.S.A.
Beamon and Fernandes (2004)	CLSC	MILP/Sensitivity analysis	√			√		√	To minimize the investment and operations cost by determining the location and allocation of capacitated warehouse and collection center.
Listeş and Dekker (2005)	OLSC	MILP/ Stochastic programming	√		√			√	To maximize the profit for sand recycling in the Netherlands by optimum location of new facility.
Salema *et al.* (2005)	CLSC	MILP	√		√		√		To minimize the total cost by determining the location of capacitated factory, warehouse and disassembly center.
Kim *et al.*(2006)	CLSC	MILP		√		√		√	To maximize the total cost saving by determining the quantity of products/parts to be processed in the remanufacturing facilities and the amount of parts to be purchased from the external suppliers.
Min *et al.*(2006a)	OLSC	MINLP/GA	√		√		√		To minimize the total cost of renting, inventory carrying, material handling, setup, and shipping costs by the optimum selection of initial collection point and centralized return centers.

SP: Single Product; MP: Multi-Product; ST: Single Time; MT: Multi-Time; CP: Capacitated; UC: Un-capacitated

Table 2.6: Literature on single objective models based on type of framework, model/methodology, number of products, time period, and capacity of facility centers (contd.)

Reference	**Type of Framework**	**Model / Methodology**	**Product**		**Time Period**		**Capacity**		**Objective**
			SP	**MP**	**ST**	**MT**	**UC**	**CP**	
Jayaraman (2006)	CLSC	Linear programming		√		√	√		To minimize the total cost per remanufactured unit by determining the optimal number of cores with a nominal quality level that is disassembled, disposed, remanufactured and acquired.
Hong *et al.*(2006b)	CLSC	MILP/ robust optimization		√	√			√	To maximize the net profit for specified deterministic parameters in different scenario.
Wang and Wen-Cheng (2007)	OLSC	MILP/ Heuristics	√		√		√		To maximize the net profit by determining the optimal location of store and recycling facility for e-waste in Taiwan
Lieckens and Vandaele (2007)	OLSC	MINLP/ Differential evolution	√		√			√	To maximize the overall profit by determining which facilities should be operated; at which capacity level; and how the flow should be assigned.
Salema *et al.* (2007)	CLSC	MILP/ Branch and bound		√	√			√	Capacitated facility location model to minimize the total cost.
Ko and Evans (2007)	CLSC	MINLP/GA based heuristics		√		√		√	Capacitated facility location model to minimize the total cost.
Lu and Bostel (2007)	CLSC	Lagrangian relaxation	√		√			√	Un-capacitated facility location model to minimize the total cost.
Üster *et al.* (2007)	CLSC	MILP/ Benders decomposition		√	√			√	To minimize the processing, transportation and fixed costs by determining optimal location of collection and remanufacturing facilities.
Listeş (2007)	CLSC	MILP	√		√			√	To minimize the total cost with the location and allocation of plant, facility centers and transportation links.

SP: Single Product; MP: Multi-Product; ST: Single Time; MT: Multi-Time; CP: Capacitated; UC: Un-capacitated

Table 2.6: Literature on single objective models based on type of framework, model/methodology, number of products, time period, and capacity of facility centers (contd.)

Reference	**Type of Framework**	**Model / Methodology**	**Product**		**Time Period**		**Capacity**		**Objective**
			SP	**MP**	**ST**	**MT**	**UC**	**CP**	
Lee and Dong (2008)	CLSC	Tabu search (TS) heuristics	√		√			√	Location-allocation model for an end-of-lease computer recovery network to minimize the total cost.
Kannan *et al.* (2008)	CLSC	GA and PSO		√		√	√		Design a multi echelon closed-loop supply chain in a build to order environment to minimize the total cost.
Min and Ko (2008)	OLSC	MILP/GA		√		√		√	To maximize the cost savings by deciding the optimal number, location and size of capacitated repair facilities/warehouses under capacity constrains and service requirements.
Srivastava (2008)	OLSC	MILP		√		√		√	To maximize the profit by determining disposition decision; and the location and capacity of collection and rework facility centers.
Aras *et al.* (2008)	OLSC	MINLP/Tabu search heuristics		√	√		√		Facility location-allocation model to find both the optimal locations of the predetermined collection centers and the optimal incentive values for different return types to maximize the total profit.
Mansour and Zarei (2008)	OLSC	Heuristics	√			√		√	Location and allocation of collection centers and dismantling centers to minimize the cost for end-of-life vehicle recovery.
Demirel and Gökçen (2008)	CLSC	MILP		√	√			√	To minimize the total cost by determining the optimal location and allocation of facility centers, as well as number of parts to be remanufactured and to be purchased from external suppliers.
Cruz-Rivera and Ertel (2009)	CLSC	MINLP/ GA based heuristics		√		√	√		Un-capacitated facility location model in order to design a collection network for end-of-life vehicles in Mexico to minimize the total cost.

SP: Single Product; MP: Multi-Product; ST: Single Time; MT: Multi-Time; CP: Capacitated; UC: Un-capacitated

Table 2.6: Literature on single objective models based on type of framework, model/methodology, number of products, time period, and capacity of facility centers (contd.)

Reference	**Type of Framework**	**Model / Methodology**	**Product**		**Time Period**		**Capacity**		**Objective**
			SP	**MP**	**ST**	**MT**	**UC**	**CP**	
Mutha and Pokharel (2009)	CLSC	MILP/Scenario analysis		√		√		√	To minimize the total cost by determining the number and location of facility centers, and the allocation of flow of used products and modules.
Lee *et al.* (2009)	CLSC	Genetic algorithm		√	√			√	To minimizing total shipping cost and fixed opening costs of the disassembly centers and the processing centers by determining the location and allocation of returning, disassembly and processing centers.
Pishvaee *et al.* (2009)	CLSC	Stochastic MILP	√		√			√	To minimize the total cost with location, allocation and transportation quantity between recovery centers
El-Sayed *et al.* (2010)	CLSC	Stochastic MILP	√			√		√	To maximize the total profit, by determining the location-allocation of facility centers; transportation; and the inventory level of goods.
Lee *et al.*(2010)	CLSC	MILP/ Stochastic programming		√	√			√	To determine the type of facility (forward processing, collection facility or hybrid facility) to build at each potential depot; their location and the quantities of products shipped to minimize the total cost.
Easwaran and Üster (2010)	CLSC	MILP/ Benders decomposition		√	√			√	To determine the locations and allocation of hybrid manufacturing/ remanufacturing centers and hybrid distribution/collection centers, to minimize the total cost of location, processing, and transportation.
Sasikumar *et al.* (2010)	OLSC	MINLP	√			√	√		To maximize the profit by determining the number of initial collection points and centralized return centers to open, their locations, and the allocation of the corresponding product flows for tire remanufacturing.
Pishvaee *et al.* (2011)	CLSC	Robust MIP	√		√			√	To minimize the total cost with location allocation and transportation quantity between facility centers.

SP: Single Product; MP: Multi-Product; ST: Single Time; MT: Multi-Time; CP: Capacitated; UC: Un-capacitated

Table 2.6: Literature on single objective models based on type of framework, model/methodology, number of products, time period, and capacity of facility centers (contd.)

Reference	**Type of Framework**	**Model / Methodology**	**Product**		**Time Period**		**Capacity**		**Objective**
			SP	**MP**	**ST**	**MT**	**UC**	**CP**	
Shi *et al.* (2011)	CLSC	Lagrangian relaxation		√	√			√	To maximize the manufacturer's expected profit by jointly determining the production quantities of brand-new products, the quantities of remanufactured products and the acquisition prices of the used products.
Özceylan and Paksoy (2012a)	CLSC	MILP	√			√		√	To determine the optimal amount of transportation of manufactured and disassembled products in a CLSC while determining the location of plants and retailers to minimize the total cost.
Kannan *et al.* (2012)	OLSC	MILP	√		√			√	Location and allocation of collection centers to minimize total cost considering collection, disposal, transportation, fixed opening, and emissions costs in a multistage reverse logistics network.
Das and Chowdhury (2012)	CLSC	MIP		√	√				To maximize the total profit of the organization by determining the optimal mix of new and recovered modules.
Mahmoudzadeh *et al.*(2013)	OLSC	MILP	√		√			√	Location and allocation of scrap yard for end-of-life vehicles in Iran to minimize the total cost.
Soleimani *et al.* (2013)	CLSC	MILP/Stochastic programming		√	√			√	Location and allocation to facility centers to maximize the profit.
Zeballos *et al.* (2014)	CLSC	MILP/ Stochastic programming		√		√		√	To minimize the expected cost (that includes facilities, purchasing, storage, transport and emissions costs) minus the expected revenue due to the products returned, from repairing and decomposition centers.
Kaya *et al.*(2014)	CLSC	MILP/ Stochastic programming		√		√		√	To minimize the total cost minus total profit by calculating the inventory level and number of products/parts at facility centers.

SP: Single Product; MP: Multi-Product; ST: Single Time; MT: Multi-Time; CP: Capacitated; UC: Un-capacitated

Table 2.6: Literature on single objective models based on type of framework, model/methodology, number of products, time period, and capacity of facility centers (contd.)

Reference	Type of Framework	Model / Methodology	Product		Time Period		Capacity		Objective
			SP	MP	ST	MT	UC	CP	
Hatefi and Jolai (2014)	CLSC	MILP/Robust Optimization	√		√			√	To minimize the nominal cost, while reducing disruption risk using the p-robustness criterion.
Soleimani and Govindan (2014)	RL	MILP/ Two-stage stochastic programming		√		√		√	To maximize total expected profit
Qiravani *et al.*(2014)	CLSC	MILP		√	√			√	Minimizing total cost of factories, distribution-collection centers, CRC centers and disposal centers
Luitel *et al.*(2014)	RL	MILP and analytic hierarchy	√					√	Compare the two methodologies and Cost minimization model
Hatefi *et al.*(2014)	CLSC	Credibility-constrained programming	√			√		√	Effectiveness of credibility-based solution approach and minimize the total cost of designed network
Soleimani and Kannan, (2014)	CLSC	MILP/PSO and GA		√		√			Design and planning with profit maximization
Özceylan *et al.* (2014)	CLSC	MINLP	√			√		√	To minimize costs of transportation, purchasing, refurbishing, and operating the disassembly workstations

SP: Single Product; MP: Multi-Product; ST: Single Time; MT: Multi-Time; CP: Capacitated; UC: Un-capacitated

Kim *et al.* (2006) developed a multi-period, multi-product mixed integer programming model for a supply planning problem in which returned products are disassembled to remanufacture. However, in the framework only refurbishment and disposal of parts is considered and the repair, reuse and recycle of products/parts is not considered. Moreover, the collection and inspection cost, transportation cost and product acquisition cost are not considered. In the model all the parameters are considered to be crisp values and uncertainty in parameters is not taken into account.

Vlachos *et al.* (2007) tackled the development of efficient capacity planning policies for remanufacturing facilities in reverse supply chains taking into account not only economic but also environmental issues. The behavior of the generic system under study is analyzed through a simulation model based on the principles of the system dynamics methodology.

Listeş (2007) presented a generic stochastic model for the design of networks comprising both supply and return channels, organized in a closed-loop system. The model accounts for a number of alternative scenarios, based on critical parameters such as demand or returns. The stochastic solution features a significant improvement in terms of average performance over the individual scenario solutions. The model is based on the branch-and-cut procedure termed as the integer L-shaped method.

Lu and Bostel (2007) proposed an un-capacitated facility location model and an algorithm based on Lagrangian heuristics, in which forward flow and reverse flows and their mutual interactions were considered simultaneously. In this model it was also assumed that (i) the product demands and available quantities of used products at the customers are known (ii) quality of remanufactured product/part is same as the new one and can be sold at the same price. Further in the proposed model inventory cost and unit cost of recycling is not considered.

Talbot *et al.* (2007) analyzed empirical evidence from a sample of 205 environmentally responsive small and medium enterprises operating in the fabricated metal products and electric/electronic products industries. A research model is developed which classified the CLSC activities into the forward and reverse supply chains activities. The results demonstrate that firms' abilities to implement CLSC environmental initiatives vary in their intensity and in their locus along the product value chain.

Demirel and Gökçen (2008) proposed an MILP model that provides the optimal values of production and transportation quantities of manufactured and remanufactured products while solving for the location of collection, disassembly and distribution facilities. Company must decide the number of products to be disassembled and the parts to be purchased from suppliers to minimize the total costs of the system. In the proposed model uncertainty in parameters is not considered, but sensitivity analysis is conducted with return rates. In the proposed model only remanufacturing and disposal is considered as product recovery options but repair, reuse and recycle is not considered. Further as the proposed model is single time period model so inventory cost is also not considered.

Lee and Dong (2008) developed a deterministic model for systematically managing forward and reverse logistics flows for end-of-lease computer products, with the objective to minimize the total cost. A two-stage heuristic approach is developed to decompose the integrated distribution networks into a location–allocation problem and a network flow problem. However, it is assumed that the model contains a single original equipment manufacturer, known number of facility centers, limited capacity at facility centers, and the recovered product is identical to new product. Fuente *et al.* (2008) proposed an integrated model for supply chain management in which forward and reverse logistics are considered simultaneously and validated it with a case study of metal mechanic sector organization.

Kusumastuti *et al.* (2008) developed a facility location-allocation model for redesigning a closed-loop service network of a computer manufacturer. They described the case study of a company providing repair services on behalf of a computer manufacturer in the Asia-Pacific region. The model considered the possibility of having the network span across several countries and multi-period planning horizons.

Kannan *et al.* (2008) designed an integrated multi-echelon forward logistics and multi-echelon closed-loop distribution inventory supply chain model for the built-to-order environment using genetic algorithm and particle swarm optimization. The proposed model is validated by considering two case studies: one for a tyre manufacturer and the other for a plastic goods manufacturer both located in southern part of India. The various assumptions in the model are: only recycling operation is considered, single unlimited capacity collection center is considered, and capacity of suppliers is considered unlimited.

Mansour and Zarei (2008) developed an RL network for end-of-life vehicles (ELVs) based on EU Directives. A multi-period reverse logistics optimization model is developed to find the number, location and the capacity of the collection centers, dismantlers and also the amount of materials flow between different facilities. The facilities involved in reverse logistics of ELVs include collection centers, dismantling centers, remanufacturers, shredders, and different recyclers for different material. The solution methodology was based on a multiple start search algorithm.

Lee *et al.* (2009) formulated a three-stage logistics model for a CLSC system to minimize the reverse logistics shipping cost and fixed cost of the disassembly centers and processing centers using genetic algorithm. Although the model can determine the optimal numbers of disassembly and processing centers, but the reuse, recycle, disposal and inventory cost is not considered in the model. It is also assumed that there is only one supplier. Lee and Dong (2009) proposed dynamic location and allocation models to cope with factors that may vary over time and influence reverse logistics network design, using stochastic programming.

Mutha and Pokharel (2009) presented a model considering the modular product structure with different disposal and recycling fractions for each module. The focus is to decide the number of facilities, their locations and allocation of corresponding flow of used products and modules at an optimal cost for a given market demand and used product returned quantities. The model assumed the demand of remanufacture products to be deterministic by the historical average. Further the recycle, disposal and remanufacturing is considered but the reuse of products is not considered in the model.

Pishvaee *et al.* (2009) developed a stochastic MILP model for single period, single product, multi-stage integrated forward/reverse logistics network design that could support both recovery and disposal activities to cope with the uncertainty in the quantity and quality of returned products, demands and variable costs. First, an efficient deterministic MILP model was developed for integrated logistics network design to avoid the sub-optimality caused by the separate design of the forward and reverse networks. Next the stochastic MILP model was developed using scenario-based stochastic approach to cope with the uncertainty.

El-Sayed *et al.* (2010) developed a multi-period, multi-echelon forward-reverse logistics network design under risk. The problem was formulated as a stochastic MILP decision model with the objective to maximize the total expected profit. Sasikumar *et al* .(2010) developed a mixed integer nonlinear programming model to maximize the profit of a multi-echelon reverse logistics network and presented a real-life case study of truck tire remanufacturing for the secondary market segment. The proposed model was solved using LINGO 8.0 optimization solver to find the location and allocation of initial collection points and centralized return centers.

Shi *et al.* (2011) studied the production planning of a multi-product closed-loop system, in which the manufacturer has two channels for supplying products: producing brand-new products and remanufacturing returns into as-new ones. Lagrangian relaxation was used to maximize the manufacturer's expected profit by jointly determining the production quantities of brand-new products, the quantities of remanufactured products and the acquisition prices of the used products, subject to capacity constraints. The proposed model considers the demand and return as uncertain and price-sensitive. Model assumes that there is no distinction between the brand-new product and the remanufactured product, which are sold together for the same price.

Pishvaee *et al.* (2011) proposed a deterministic MILP model for closed-loop supply chain network design and extended the model to develop a robust counterpart of the proposed MILP model was also developed to cope with the uncertainty in returned products, demands for recovered products and transportation cost. Numerical tests show that the proposed model is able to handle uncertainty in parameters and generate robust optimal solutions. The objective of model was to minimize the total cost with location-allocation and transportation quantity between facility centers. In the proposed model binary variables are considered only for collection, recovery and redistribution centers. Moreover it is single time period model so inventory cost is not considered.

Kannan *et al.* (2012) proposed a mixed-integer linear programming model to minimize the carbon footprint of reverse logistics network and validated the model by a case study from the plastic sector. The single product and single time model employed reverse logistics activities to recover used products, hence combined the location/transportation decision problem. Özceylan and Paksoy (2012a) proposed a mixed integer mathematical model for the CLSC network that includes both forward and reverse flow with multi-periods and multi-parts. The proposed model provides the optimal values of manufactured and disassembled products in the CLSC while determining the location of plants and retailers. However, in the proposed model the uncertainty in parameters is not considered.

Mahmoudzadeh *et al.* (2013) proposed a MILP model to determine optimal location of scrap yards over the country as well as their optimal allocations and material flows for the recovery of ELVs in Iran. Hasanov *et al.* (2013) developed a mathematical model for a closed-loop supply chain system with energy, transportation and disposal costs. It also proposed a framework for studying lot-sizing policies of production processes. The numerical results emphasize that accounting for energy, transportation and disposal costs in supply chain modeling increases the sustainability of a production-inventory system. Soleimani *et al.* (2013) cope with the design and planning problem of a CLSC in a two-stage stochastic structure using three types of risk measures: mean absolute deviation, value at risk and conditional value at risk. Consequently, three types of mean-risk models are developed as objective functions and decision-making procedures are undertaken based on the expected values and risk adversity criteria.

Zeballos *et al.* (2014) proposed a multi-period, multi-product MILP model for CLSC to minimizes the expected cost (that includes facilities, purchasing, storage, transport and emissions costs) minus the expected revenue due to the amount of products returned, from repairing and decomposition centers to the forward network. The effects of uncertainty in demand and supply are considered by multiple scenarios with known probability of occurance. Kaya *et al.* (2014) developed a MILP model for capacity planning, production and inventory decisions in a generic reverse supply chain under uncertain demand and returns for modular products. They proposed a two-stage stochastic optimization and robust optimization approaches to analyze the system behavior.

Multi-objective models

In spite of a considerable amount of research already carried out on supply chain network design, in recent years, there has been a growing awareness of incorporating environmental and social indicators in the supply chain activities (Özceylan and Paksoy, 2012a). Various strategic and operational aspects of CLSC such as forecasting, production planning and control, and inventory control have been investigated in the last decade. Few papers are available on multi-objective optimization of economic and environmental factors and a few papers on the multi-objective optimization including social factors. Table 2.7 provides a literature review of multi-objective CLSC models based on objective function, model/methodology, number of products, single time/multi-time period and capacitated/un-capacitated facility centers.

Integration of life cycle analysis with logistic optimization was described by Bloemhof-Ruwaard *et al.*(1996). Life cycle assessment was used to obtain an environmental performance indicator for each process. These indicators were used as inputs for a linear programming network flow model to find optimal design of the pulp and paper network with the lowest environmental impact. Krikke *et al.* (2003) developed a quantitative model to support an optimal product design as well as the optimal locations and allocation of goods in the logistics system. Environmental impact was measured in terms of energy used and waste generated. Economic costs were modeled as linear functions of volumes with a fixed set-up component for facilities. The model was applied to a real life R&D data of a Japanese consumer electronics company. The model was considered for different scenarios using different parameter settings such as centralized versus decentralized logistics, alternative product designs, varying return quality and quantity, and potential environmental legislation based on producer responsibility.

Sheu *et al.* (2005) formulated a linear multi-objective programming model to maximize the profit of forward and reverse supply chain in green-supply chain management. Factors such as the used-product return ratio and subsidies from governmental organizations for RL are considered in the model formulation. Results of the particular case study shows that using the proposed model, the chain-based aggregate net profits can be improved by 21.1%, compared to the existing operational performance.

Lee *et al.* (2007b) developed a multi-objective model for an integrated reverse and forward logistics network design from the perspective of third-party logistics provider. Similarly, Lee *et al.* (2007a) extended the previous work to a multi-product problem. Lee *et al.* (2012) tried to adopt and redesign an integrated forward-reverse logistics system for a large third-party logistics provider.

Table 2.7: Literature on multi-objective models based on model/methodology, number of products, time period, and capacity of facility centers

Reference	**Type of Framework**	**Model/ Methodology**	**Product**		**Time Period**		**Capacity**		**Objective Function**		
			SP	**MP**	**ST**	**MT**	**UC**	**CP**	**Economical**	**Environmental**	**Social**
Krikke *et al.* (2003)	CLSC	MILP/ weighted sum method		√	√		√		Facility location-allocation model to minimize the economical impact of CLSC for refrigerator of a Japanese manufacturing company.	Minimize the environmental impact in terms of energy use for transportation, processing and waste generated.	------------------
Pati *et al.* (2008)	OLSC	Mixed integer Goal Programming		√	√			√	Determine the facility location, route and flow of different varieties of recyclable wastepaper to: • Reduce RL costs; • Improve the product quality through increased segregation at the source.	• Environmental benefits through increased wastepaper recovery.	------------------
Dehghanian and Mansour (2009)	CLSC	Genetic Algorithm	√		√		√		To maximize economic benefits by deciding the optimum location of plant and the shipment from collection centers to each installed plant.	To minimize negative environmental impacts using Eco-indicator.	To maximize social benefits by considering employment, damage to workers, product risk and local development as the elements of social development.

SP: Single Product; MP: Multi-Product; ST: Single Time; MT: Multi-Time; CP: Capacitated; UC: Un-capacitated

Table 2.7: Literature on multi-objective models based on model/methodology, number of products, time period, and capacity of facility centers (contd.)

Reference	**Type of Framework**	**Model/ Methodology**	**Product**		**Time Period**		**Capacity**		**Objective Function**		
			SP	**MP**	**ST**	**MT**	**UC**	**CP**	**Economical**	**Environmental**	**Social**
Özceylan and Paksoy (2012b)	CLSC	MILP/ L-constraint method		√		√	√		Determine the optimal number of parts to be processed at remanufacturing facilities and number of parts to be purchased from the external suppliers to: • Minimize manufacturing and distribution costs • Minimize total fixed costs of plants and retailers	---------------	---------------
Pishvaee and Razmi (2012)	OLSC	MILP/ ε-constraint method	√		√			√	To minimize total cost by capacitated facility location allocation model.	To minimize the environmental impact using Eco-indicator 99	--------------
Amin and Zhang (2013a)	CLSC	MILP/ε-constraint; weighted sum; stochastic method		√	√			√	Determine the number of products at each node of CLSC network: • To minimizing the total cost of CLSC network.	To maximize the effect of using environmental friendly materials and clean technology.	--------------

SP: Single Product; MP: Multi-Product; ST: Single Time; MT: Multi-Time; CP: Capacitated; UC: Un-capacitated

Table 2.7: Literature on multi-objective models based on model/methodology, number of products, time period, and capacity of facility centers (contd.)

Reference	**Type of Framework**	**Model/ Methodology**	**Product**		**Time Period**		**Capacity**		**Objective Function**		
			SP	**MP**	**ST**	**MT**	**UC**	**CP**	**Economical**	**Environmental**	**Social**
Pishvaee *et al.* (2010)	CLSC	MILP	√		√			√	Determine the optimum location, allocation and capacity of facility centers to: - Minimize the total costs, - Maximize the responsiveness of logistics network.	---------------	---------------
Harraz and Galal (2011)	OLSC	Mixed Integer Goal Programming		√	√			√	Determine the optimum number and location of capacitated facility centers, as well as the corresponding flow of assemblies and parts to the different end of life options: - To maximize the profit of the organization by.	To minimize the disposal by maximizing the reuse of items	Refund to customers is considered as the social element of sustainability and integrated with economical objective
Amin and Zhang (2012)	CLSC	MILP		√	√			√	To determine the parts and products at the nodes of CLSC network, and to selects the best suppliers and refurbishing sites to: - Maximize the profit - Maximize the weight of supplier - Minimize the defect rate.	-------------------	-------------------

SP: Single Product; MP: Multi-Product; ST: Single Time; MT: Multi-Time; CP: Capacitated; UC: Un-capacitated

Table 2.7: Literature on multi-objective models based on model/methodology, number of products, time period, and capacity of facility centers (contd.)

Reference	Type of Framework	Model/ Methodology	Product		Time Period		Capacity		Objective Function		
			SP	**MP**	**ST**	**MT**	**UC**	**CP**	**Economical**	**Environmental**	**Social**
Amin and Zhang (2013b)	CLSC	Mixed integer non-linear programming (MINLP)		√	√			√	Determine the number of products to be manufactured, collected, disassembled, and sent to remanufacturing subcontractors, and the units of parts to be disposed of, refurbished, and purchased from suppliers, to: • Minimize the total cost. • Maximize the weight of suppliers, refurbishing sites and remanufacturing sub-contractors. • Minimize the defect rate. • Maximize the on-time delivery.		
Özkır and Başlıgil (2013)	CLSC	MILP/ GAMS		√		√		√	To determine the optimal number and location of facilities, and determine the optimal transportation, production and purchasing quantities, through. • Maximize CLSC profit function.		• Maximize satisfaction level of stakeholders, • Maximize satisfaction degrees of customers
Özceylan and Paksoy (2014)	CLSC	MINLP		√		√		√	Determine the amounts of goods flowing on the forward and reverse chains to: • Minimization transportation costs • Minimization purchasing costs • Minimization refurbishing costs. • Minimization fixed costs.		

SP: Single Product; MP: Multi-Product; ST: Single Time; MT: Multi-Time; CP: Capacitated; UC: Un-capacitated

Table 2.7: Literature on multi-objective models based on model/methodology, number of products, time period, and capacity of facility centers (contd.)

Reference	**Type of Framework**	**Model/ Methodology**	**Product**		**Time Period**		**Capacity**		**Objective Function**		
			SP	**MP**	**ST**	**MT**	**UC**	**CP**	**Economical**	**Environmental**	**Social**
Ramezani *et al.*(2014)	CLSC	MILP		√		√		√	• Maximization of profit, • Minimization of delivery time, and • Maximization of quality		
Fallah-Tafti *et al* (2014)	CLSC	MILP		√		√		√	Minimization of total costs, Maximization of supplier's ranks and Minimization of total delivery time		
Devika *et al.*(2014)	CLSC	MILP/ Metaheuristic	√		√			√	Minimize cost/maximize the profit	Minimization of environmental impact	Maximize the social benefits

SP: Single Product; MP: Multi-Product; ST: Single Time; MT: Multi-Time; CP: Capacitated; UC: Un-capacitated

Frota Neto *et al.* (2008) proposed a model to minimize cumulative energy demand and wastes in addition to traditional economic objective for end-of-life electrical and electronic equipment recycling network. Frota Neto *et al.* (2009) proposed a methodology for assesing the eco-efficiency of logistics networks. The algorithm is designed for the multi-objective linear problem with three objectives: minimize costs, cumulative energy demand and waste in a reverse logistics network.

Dehghanian and Mansour (2009) proposed the design of a three-objective sustainable recovery network to maximize economic and social benefits, and minimize negative environmental impacts. Life cycle analysis has been applied to investigate the environmental impact of different end-of-life options. Employment, damage to workers, product risk, and local development were considered as the indicators for social development, which were normalized to obtain a single social indicator for different EOL activities using AHP. This indicator indicates the social impact of treating EOL product in each EOL option. A case study scrap tires in Iran has been considered. Pareto-optimal solutions have been used to provide the trade off information about the three objectives.

Pishvaee *et al.* (2010) proposed a model for integrated logistics network design to avoid the sub-optimality caused by a separate, sequential design of forward and reverse logistics networks. A bi-objective mixed integer programming formulation was proposed to minimize the total costs and maximize the responsiveness of the logistics network. An efficient multi-objective memetic algorithm was developed to find the set of non-dominated solutions.

Lee *et al.* (2010) proposed the design of a sustainable logistics network by deciding the type of facility to be built at each facilities depot using stochastic programming. They introduced the concept of hybrid facility center to handle both forward and return flow of products. Easwaran and Üster (2010) proposed a multi-product closed-loop logistics network design problem with hybrid manufacturing/remanufacturing facilities and finite-capacity hybrid distribution/collection centers to serve a set of retail locations. First, a mixed integer linear program is presented that determines the optimal solution that characterizes facility locations along with the integrated forward and reverse flows such that the total cost of facility location, processing, and transportation associated with forward and reverse flows in the network is minimized. Second, a solution method is devised based on Benders' decomposition with strengthened Benders' cuts for improved computational efficiencies. In the model a remanufactured product perfectly substitutes for a new product, in terms of quality and warranty. Harraz and Galal (2011) presented the design of a sustainable recovery network for end-of-life vehicles in Egypt using goal programming without considering the uncertainty in parameters. The refund to customers was considered as the social element of sustainability.

Wang and Huang (2012) presented a multi-objective demand-driven product disassembly mechanism and robust programming approach in a CLSC system. The objective of the model was to determine a robust decision for recycle volume and timing of each type of end-of-life product, as well as recovery strategies. A two-stage robust programming model was developed, such that multiple products with a hierarchical product structure are disassembled to satisfy uncertain demands in multiple periods. The uncertainty of demand was characterized as a series of distinct scenarios.

Özceylan and Paksoy (2012a) proposed a new mixed integer mathematical model for a multi-period and multi-part CLSC network. Scenario analysis was done by varying the percentage of product recovered under different recovery options. Özceylan and Paksoy (2012b) proposed a fuzzy multi-objective MILP model to minimize the total cost of manufacturing and the total fixed cost of plants and retailers. The values of capacity, demand and reverse rates have been mapped with fuzzy numbers. Amin and Zhang (2012) proposed a multi-objective model to minimizes defect rates, and maximize profit and weights of suppliers using compromise programming method. However, refund to customer, transportation cost and inventory cost were not considered in the model.

Pishvaee and Razmi (2012) presented a fuzzy multi-objective mathematical programming to minimize the total cost and environmental impact of an integrated supply chain. They presented a case of an Iranian single use medical needle and syringe manufacturer. Amin and Zhang (2013a) proposed a multi-objective facility location model for CLSC network under uncertain demand and return to minimize the total cost and maximize the effect of using environmental friendly materials and clean technology. The uncertainty in demand and return is analyzed using scenario analysis.

Amin and Zhang (2013b) proposed a three stage for CLSC configuration under uncertainty. In the first stage, suppliers, remanufacturing subcontractors, and refurbishing sites are evaluated based on a new quality function deployment (QFD) model. In addition, the fuzzy sets theory is utilised to overcome the uncertainty in the decision-making process. In the second stage, the closed-loop supply chain network is configured by a stochastic mixed-integer nonlinear programming model to determine the units of products to be manufactured, collected, disassembled, and sent to remanufacturing subcontractors, and the units of parts to be disposed of, refurbished, and purchased from suppliers under uncertain demand. The objective function is the maximisation of the expected profit. Finally in the third stage, suppliers, remanufacturing subcontractors, and refurbishing sites are selected and order allocation is determined using multi-objective MILP model.

Kannan *et al.* (2013) presented an integrated approach, of fuzzy multi attribute utility theory and multi-objective programming, for rating and selecting the best green suppliers according to economic and environmental criteria and then allocating the optimum order quantities among them. The objective of the mathematical model is simultaneously to maximize the total value of purchasing and to minimize the total cost of purchasing.

Özkır and Başlıgil (2013) proposed a multi-objective CLSC model in an uncertain environment to seek the optimal number of facilities and their location and determined the optimal transportation, production and purchasing quantities. They deduced three level goal formulations as, (i) maximizing the satisfaction level of CLSC stakeholders, (ii) maximizing the satisfaction degrees of customers and (iii) maximizing the total CLSC profit function. The uncertainty in demand, return and price of the return product was presented by triangular fuzzy numbers. Qiang *et al.* (2013) proposed an algorithm for CLSC network design to show the effects of competition, distribution channel investment, yield and conversion rates, combined with uncertainties in demand, on equilibrium quantity transactions and prices. Nikolaou *et al.* (2013) proposed an integrated model for introducing corporate social responsibility and sustainability issues in reverse logistics systems as a means of developing a complete performance framework model.

Özceylan and Paksoy (2014) proposed a fuzzy multi-objective mixed-integer non-linear programming (MINLP) model that considers the imprecise nature of critical parameters such as cost coefficients, capacity levels, market demands and reverse rates. The proposed fuzzy model is converted into an auxiliary crisp multi-objective mixed-integer non-linear programming model by applying weighted average method (Lai and Hwang, 1992) and hybrid method (Pishvaee and Torabi, 2010). They also compared the three interactive fuzzy methods that convert the auxiliary crisp multi-objective MINLP models into the equivalent single objective MINLP models on a CLSC network design problem.

Choudhary *et al.* (2015) proposed a quantitative optimization model for integrated forward–reverse logistics with carbon-footprint considerations, by integrating the carbon emission into a quantitative operational decision-making model with regard to facility layout decisions. Subulan *et al.*(2015) developed a multi-objective, multi-echelon, multi-product, and multi-period logistics network design model in a more holistic manner while also considering environmental issues.

2.4.3. Based on product recovery options

Product recovery process is one of the very important activities in reverse logistics. Repair, reuse, refurbish, remanufacture, recycle and disposal are the major product recovery processes in reverse logistics, as discussed in the elements of reverse logistics. Different models have used different set of product recovery processes in their model for reverse logistics. Table 2.8 provides the literature on network models, based on recovery options opted by them in their models.

Table 2.8: Literature on reverse logistics models based on product recovery options

Reference	**Product Recovery Options**				
	Reuse	**Recycle**	**Remanufacture**	**Refurbish**	**Disposal**
Kroon and Vrijens (1995)	√				
Jayaraman *et al.* (1999)			√		
Krikke *et al.*(1999b)			√		
Fleischmann *et al.*(2001)		√	√		
Krikke *et al.* (2003)		√	√		√
Jayaraman *et al.*(2003)				√	
Realff *et al.* (2004)		√			
Listeş and Dekker (2005)		√			
Listeş and Dekker (2005)		√			
Kim *et al.*(2006)				√	√

Table 2.8: Literature on reverse logistics models based on product recovery options (contd.)

Reference	**Product Recovery Options**				
	Reuse	**Recycle**	**Remanufacture**	**Refurbish**	**Disposal**
Wang and Wen-Cheng (2007)		√			√
Ko and Evans (2007)			√		
Lu and Bostel (2007)			√		√
Üster *et al.* (2007)					
Listeş (2007)			√		√
Lieckens and Vandaele (2007)	√			√	√
Min and Ko (2008)	√				
Pati *et al.*(2008)		√			
Mansour and Zarei (2008)		√			
Demirel and Gökçen (2008)			√		√
Mutha and Pokharel (2009)		√	√		√
Lee *et al.* (2009)	√	√	√		√
Pishvaee *et al.* (2009)			√		√
Dehghanian and Mansour (2009)	√	√			√
Sasikumar *et al.* (2010)			√		
Pishvaee *et al.*(2010)					√
El-Sayed *et al.* (2010)	√	√	√		√
Lee *et al.*(2010)			√		
Easwaran and Üster (2010)			√		
Pishvaee *et al.*(2011)			√		√
Harraz and Galal (2011)	√	√		√	√
Kannan *et al.* (2012)		√			√
Özceylan and Paksoy (2012a)	√			√	√
Amin and Zhang (2012)				√	√
Özceylan and Paksoy (2012b)	√			√	√
Pishvaee and Razmi (2012)		√			√
Wang and Huang (2012)	√	√	√		√
Özkır and Başlıgil (2013)	√	√		√	√
Amin and Zhang (2013a)			√		
Mahmoudzadeh *et al.*(2013)		√			

2.4.4. Based on different costs

Reverse supply chain is associated with many costs like collection cost, sorting/testing cost, disassembly cost, remanufacturing cost, transportation cost, inventory cost, fixed cost, etc. Different models considered different set of costs in their model. Table 2.9 provides a review of research papers based on different costs considered in the model.

Table 2.9: Literature on reverse logistics models based on type of costs considered

References	**Costs considered in the reverse logistics model**														
	Raw material cost	**Production cost**	**Product acquisition cost**	**Collection cost**	**Sorting/testing cost**	**Disassembly cost**	**Refurbishing cost**	**Remanufacturing cost**	**Disposal cost**	**Recycling cost**	**Fixed/Set-up cost**	**Transportation cost**	**Inventory cost**	**Processing cost**	**Penalty Cost**
Kroon and Vrijens (1995)				√							√	√			
Jayaraman *et al.* (1999)			√				√				√		√		
Krikke *et al.*(1999b)							√					√	√		
Fleischmann *et al.*(2001)									√		√	√			
Jayaraman *et al.*(2003)											√	√			
Krikke *et al.*(2003)											√	√		√	
Realff *et al.* (2004)				√						√	√	√	√		
Beamon and Fernandes (2004)											√	√	√		
Listeş and Dekker (2005)										√	√	√			
Salema *et al.*(2005)											√	√			
Min *et al.*(2006a)											√	√	√		
Kim *et al.*(2006)	√					√	√		√		√		√		√
Jayaraman (2006)	√		√			√		√	√				√		
Min *et al.*(2006b)											√	√	√	√	
Listeş (2007)		√			√				√		√	√		√	√

Table 2.9: Literature on reverse logistics models based on type of costs considered (contd.)

References	Costs considered in the reverse logistics model														
	Raw material cost	**Production cost**	**Product acquisition cost**	**Collection cost**	**Sorting/testing cost**	**Disassembly cost**	**Refurbishing cost**	**Remanufacturing cost**	**Disposal cost**	**Recycling cost**	**Fixed/Set-up cost**	**Transportation cost**	**Inventory cost**	**Processing cost**	**Penalty Cost**
Wang and Wen-Cheng (2007)										-√	√	√			
Lieckens and Vandaele (2007)									√		√	√	√		√
Salema *et al.*(2007)		√							√		√	√		√	√
Ko and Evans (2007)											√	√	√		
Lu and Bostel (2007)		√						√	√		√	√			
Üster *et al.* (2007)		√		√		√		√			√	√			
Pati *et al.*(2008)				√	√				√		√	√	√		
Aras *et al.*(2008)			√	√								√			
Lee and Dong (2008)				√							√	√			
Mansour and Zarei (2008)											√	√	√		
Demirel and Gökçen (2008)	√	√		√		√			√		√	√			
Mutha and Pokharel (2009)		√	√						√		√	√	√	√	
Dehghanian and Mansour (2009)											√	√			
Pishvaee *et al.* (2009)		√							√		√	√		√	√
Lee *et al.* (2009)											√	√		√	
Lee *et al.* (2010)											√	√		√	
Sasikumar *et al.* (2010)				√				√		-√	√	√	√		
Easwaran and Üster (2010)		√		√				√			√	√		√	
Pishvaee *et al.*(2010)											√	√			
El-Sayed *et al.* (2010)	√	√			√	√		√	√	√	√	√	√		√

Table 2.9: Literature on reverse logistics models based on type of costs considered (contd.)

References	Costs considered in the reverse logistics model														
	Raw material cost	**Production cost**	**Product acquisition cost**	**Collection cost**	**Sorting/testing cost**	**Disassembly cost**	**Refurbishing cost**	**Remanufacturing cost**	**Disposal cost**	**Recycling cost**	**Fixed/Set-up cost**	**Transportation cost**	**Inventory cost**	**Processing cost**	**Penalty Cost**
Harraz and Galal (2011)			√	√	√	√	√		√	-√	√	√			
Pishvaee *et al.*(2011)											√	√			√
Özceylan and Paksoy (2012a)								√			√	√		√	
Amin and Zhang (2012)	√	√				√	√		√		√				
Özceylan and Paksoy (2012b)	√						√				√	√			
Wang and Huang (2012)			√	√	√	√		√	√	√	√		√		√
Kannan *et al.* (2012)				√					√		√	√			
Amin and Zhang (2013a)		√							√		√	√		√	
Mahmoudzadeh *et al.*(2013)											√	√			
Özkır and Başlıgil (2013)	√	√	√			√	√		√		√	√	√		

2.4.5. Based on binary decision locations

Most of the reverse logistics models are associated with the location-allocation of different facility centers; like collection centers, disassembly centers, refurbishing centers, etc. Location and allocation to these facility centers is decided with the help of binary numbers, i.e. if the binary variable is '1' then facility center is located, and if its value is '0' then facility center is not located. Different models have considered different set of binary locations based on the problem. Table 2.10 provides a literature review of reverse logistics models based on the binary locations considered in the model.

Table 2.10: Literature on reverse logistics models based on binary location nodes

	Facility Location Nodes (Binary Decision Variables)														
References	**Manufacturing units**	**Distributors**	**Retailers**	**Customer zones**	**Collection centers**	**Repair centers**	**Disassembly centers**	**Refurbishing centers**	**Remanufacturing centers**	**Recovery facilities**	**Recycle centers**	**Disposal centers**	**External suppliers**	**Warehouses**	**Redistribution centers**
Kroon and Vrijens (1995)					√										
Jayaraman *et al.* (1999)					√					√					
Fleischmann *et al.*(2001)	√						√							√	
Jayaraman *et al.*(2003)					√			√							
Beamon and Fernandes (2004)					√									√	
Realff *et al.* (2004)					√										
Listeş and Dekker (2005)															
Salema *et al.*(2005)	√						√							√	
Listeş and Dekker (2005)					√						√				
Min *et al.*(2006a)					√										
Min *et al.*(2006b)				√	√										
Kim *et al.*(2006)							√	√							
Wang and Wen-Cheng (2007)					√						√				
Salema *et al.*(2007)	√						√							√	
Ko and Evans (2007)						√								√	
Lu and Bostel (2007)	√								√						
Listeş (2007)	√			√						√					
Üster *et al.* (2007)					√				√						
Lieckens and Vandaele (2007)								√							
Aras *et al.*(2008)					√										
Lee and Dong (2008)															
Mansour and Zarei (2008)					√						√				
Demirel and Gökçen (2008)		√			√		√								
Aras *et al.* (2008)					√										
Pishvaee *et al.* (2009)	√											√			
Lee *et al.* (2009)							√			√					
Mutha and Pokharel (2009)	√								√					√	
Dehghanian and Mansour (2009)	√														

Table 2.10: Literature on reverse logistics models based on binary location nodes (contd.)

References	Facility Location Nodes (Binary Decision Variables)														
	Manufacturing units	**Distributors**	**Retailers**	**Customer zones**	**Collection centers**	**Repair centers**	**Disassembly centers**	**Refurbishing centers**	**Remanufacturing centers**	**Recovery facilities**	**Recycle centers**	**Disposal centers**	**External suppliers**	**Warehouses**	**Redistribution centers**
Lee *et al.*(2010)	√				√										
Pishvaee *et al.*(2010)	√	√			√							√			
Sasikumar *et al.* (2010)					√										
El-Sayed *et al.* (2010)		√					√			√		√	√		√
Pishvaee *et al.*(2011)					√					√					√
Harraz and Galal (2011)							√	√							
Kannan *et al.* (2012)					√										
Amin and Zhang (2012)							√	√				√			
Özceylan and Paksoy (2012a)	√		√										√		
Özceylan and Paksoy (2012b)	√		√										√		
Pishvaee and Razmi (2012)	√				√										
Wang and Huang (2012)															
Özkır and Başlıgil (2013)	√	√			√					√					
Amin and Zhang (2013a)	√				√										
Mahmoudzadeh *et al.*(2013)											√				

2.4.6. Based on methods to handle uncertainty

Reverse supply chains generally, operate in the presence of different types of uncertainties in different kind of sources. Demand uncertainty (Chen *et al.*, 2007; Efendigil *et al.*, 2009; Petrovic *et al.*, 2008), lead time uncertainty (Petrovic, 2001), supply uncertainty, inventory holding and backorder cost uncertainty (Giannoccaro *et al.*, 2003), manufacturing cost uncertainty (Zhu *et al.*, 2007) have been investigated in supply chain modeling by different researchers.

Wang and Huang (2012) described the three methods to handle uncertainty in parameters i.e. sensitivity analysis, stochastic programming and robust programming. Other than this literature has also suggested the use of fuzzy mathematical programming to handle the uncertainty in parameters of reverse supply chain (Alimoradi *et al.*, 2011; Amid *et al.*, 2006; Mula *et al.*, 2010; Özceylan and Paksoy, 2014; Pishvaee and Torabi, 2010). The following text provides a brief discussion on these methods to handle uncertainty.

Sensitivity/scenario analysis

Sensitivity analysis is a standard way to tackle uncertainty for a single or multiple parameters (Morgan, 1992). It gives an insight that how the solution changes if one or more input parameters are varied. This approach can be extended by introducing scenarios for the input parameters. Each scenario is associated with a probability level representing the decision maker's expectation of the occurrence of a particular scenario (Gupta and Maranas, 2003). The drawback of this approach is that it provides solutions which are optimal for only for one set of parameters (Listeş and Dekker, 2005). Some studies have employed sensitivity analysis to investigate the effects of the parameter disturbance on the optimal decisions. Kim *et al.* (2006) did the sensitivity analysis for cost saving with respect to the capacity of collection center, disassembly center and refurbishing center; Mutha and Pokharel (2009) did the scenarios analysis by varying the quantity of return, changing the capacity of processing centers, changing the disposal to recycle percentage; Özceylan and Paksoy (2012a) did the scenario analysis by varying the percentage of product recovery options.

Stochastic programming

In stochastic programming all the uncertain parameters are described by random variables with a probability distribution, and then considered into the mathematical model (Wang and Huang, 2012). According to Kall and Wallace (1994) stochastic programming techniques offer more flexibility for handling uncertainty and can turn up with solutions that cannot be found by scenario analysis. It provides a compromised solution against various future scenarios. Amin and Zhang (2013a), Lee *et al.*(2010), Lieckens and Vandaele (2007), Listeş and Dekker (2005), etc. have used the stochastic programming in their models. But following are some drawbacks of stochastic programming as mentioned by Pishvaee *et al.*(2011):

(i) In many real cases there is no enough historical data for the uncertain parameters, to obtain the actual probability distributions of the uncertain parameters.

(ii) In stochastic optimization, the solution is immunized in some probabilistic sense to stochastic uncertainty and thus the solution could be infeasible for some realizations. Although this happens with very small probability but it could brings high costs.

(iii) In recent works the uncertainty is modeled through scenario-based stochastic programming. In this large number of scenarios are used to represent the uncertainty, which can lead to computationally challenging problems.

Robust optimization

Robust optimization is a type of stochastic programming technique proposed by Mulvey *et al.* (1995). In a robust approach a number of scenarios is identified and a solution is sought which minimizes the maximum deviation to the optimal objective values of the individual scenarios (Listeş, 2007). In order to obtain the robust solutions, there is always a trade-off between solution robustness and model robustness. Solution robustness means that the robust solution has less variability in objective function values under different scenarios. Model robustness means that the robust solution remains almost feasible if input parameters are changed (Wang and Huang, 2012). However, the solution time is quite large. Wang and Huang (2012), Pishvaee *et al.*(2011), Hong *et al.*

(2006b), Realff *et al.* (2004) are few of the robust optimization model in reverse supply chain management.

Fuzzy-based approach

In the fuzzy-based approach the uncertain parameters are considered as fuzzy numbers with accompanied membership functions. Principal difference between the stochastic and fuzzy optimization approaches is the way uncertainty is modeled. In the stochastic programming, uncertainty is modeled through discrete or continuous probability functions. On the other hand, fuzzy programming considers random parameters as fuzzy numbers and constraints are treated as fuzzy sets. Özkır and Başlıgil (2013), Amin and Zhang (2012), Özceylan and Paksoy (2012b), Pishvaee and Razmi (2012) have considered the uncertainty in parameters with fuzzy numbers in reverse supply chain.

Table 2.11 provides a brief literature review of the models using sensitivity/scenario analysis, stochastic programming, robust optimization, fuzzy mathematics; and the corresponding uncertain parameters. Wang and Huang (2012) provides a comparison of sensitivity analysis, stochastic programming and robust optimization techniques. Extending the work of Wang and Huang (2012), a comparison of sensitivity analysis, stochastic programming, robust optimization and fuzzy programming is presented in Table 2.12.

Table 2.11: Literature review of reverse logistics models based on method to handle uncertainty in parameters

Reference	Methods to handle uncertainty				Uncertain parameters
	Sensitivity/ scenario analysis	**Stochastic programming**	**Robust optimization**	**Fuzzy mathematics**	
Jayaraman *et al.* (1999)	√				Sensitivity analysis is done for total cost with respect to demand of remanufactured products
Fleischmann *et al.*(2001)	√				Sensitivity analysis is done to study the impact of return rate on the total cost.
Krikke *et al.*(2001)	√				Sensitivity analysis is done to study the effect of rate of return, recovery feasibility and recovery targets.
Realff *et al.* (2004)			√		Uncertainty of time-delay in re-manufacturing and returns, uncertainty of system cost parameters, uncertainty of customers' demand disturbances
Beamon and Fernandes (2004)	√				Sensitivity analysis is done to study the effect of percentage of return in good quality, time horizon and interest rate.
Listeş and Dekker (2005)		√			Stochastic programming is done to consider the uncertainty in demand and supply rate.
Kim *et al.*(2006)	√				Sensitivity analysis is done for cost saving with respect to the capacity of collection center, disassembly center and refurbishing center
Hong *et al.* (2006b)			√		Participation rate, utilization of collection infrastructure, CPU usability percentage, television reusability percentage
Lieckens and Vandaele (2007)		√			Stochastic programming is done to consider the uncertainty in lead time.
Salema *et al.*(2007)		√			Stochastic programming is done to consider the uncertainty in demand and supply of return products.

Table 2.11: Literature review of reverse logistics models based on method to handle uncertainty in parameters (contd.)

Reference	**Methods to handle uncertainty**				**Uncertain parameters**
	Sensitivity/ scenario analysis	**Stochastic programming**	**Robust optimization**	**Fuzzy mathematics**	
Listeş (2007)		√			Stochastic programming is done to consider the uncertainty in quantity of demand and return in the market.
Chouinard *et al.* (2008)		√			The randomness related with recovery, processing and demand volumes in a closed-loop supply chain design problem.
Pati *et al.*(2008)	√				Sensitivity analysis is done to study the effect of waste paper recovery rate at source and degree of segregation at source.
Aras *et al.* (2008)	√				Sensitivity analysis is done to study the effect of vehicle operating cost and vehicle capacity.
Demirel and Gökçen (2008)	√				Sensitivity analysis is done to study the effect of low and medium rate of return as well as varying the number of facility centers on total cost.
Mutha and Pokharel (2009)	√				Scenarios analysis is done by varying the quantity of return, changing the capacity of processing centers, changing the disposal to recycle percentage.
Pishvaee *et al.* (2009)		√			Stochastic programming is done to consider the uncertainty in uncertain demand, return and variable cost.
El-Sayed *et al.* (2010)		√			Stochastic programming is done to study the uncertainty in demand and return quantities.
Lee *et al.*(2010)		√			Demand of forward products and supply of returned products at customers are considered as stochastic parameters with known distribution
Pishvaee *et al.* (2011)			√		Robust optimization is done to consider the uncertainty in demand, return and transportation cost.
Shi *et al.* (2011)	√				Sensitivity analysis is done to study the uncertainty in demand and supply rate.
Özceylan and Paksoy (2012a)	√				Scenarios analysis is done with percentage of product recovery options.

Table 2.11: Literature review of reverse logistics models based on method to handle uncertainty in parameters (contd.)

Reference	Methods to handle uncertainty				Uncertain parameters
	Sensitivity/ scenario analysis	**Stochastic programming**	**Robust optimization**	**Fuzzy mathematics**	
Amin and Zhang (2012)				√	Supplier related, part related and process related parameters are considered fuzzy to evaluate the external suppliers.
Özceylan and Paksoy (2012b)				√	Triangular fuzzy numbers (TFN's) are used to handle the uncertainty in demand, capacity and reverse rates.
Pishvaee and Razmi (2012)				√	Demand, return, fixed cost, transportation cost, processing cost, capacity at facility centers and environmental impact.
Wang and Huang (2012)			√		The uncertainty of demand is characterized as a series of distinct scenarios in a two-stage robust programming model, for the purpose of finding a compromised decision
Das and Chowdhury (2012)	√				Increase of recovered product demand, change in demand of different quality level on the total profit.
Amin and Zhang (2013a)		√			Stochastic programming is done to consider the uncertainty in demand and return of products.
Özkır and Başlıgil (2013)				√	Price of the product, demand and return are considered uncertain in the model.
Soleimani *et al.* (2013)		√			Demand, return and price
Özceylan and Paksoy (2014)				√	Capacities, demands, cost coefficients, and reverse rates are assumed to be imprecise in nature and modeled with Triangular Fuzzy Numbers (TFN).
Zeballos *et al.* (2014)		√			Demand and supply
Kaya *et al.*(2014)		√			Demand and return

Table 2.12: Comparison of the methods to handle uncertainty in parameters

Comparative Parameters	**Sensitivity analysis**	**Stochastic programming**	**Robust optimization**	**Fuzzy Programming**
Objective	Finds the key parameter that influences the optimal solution	Determines a compromised solution to achieve the highest expected performance	Determines a robust solution that is less sensitive in uncertain environments	Determines a optimal solution with an associated degree of feasibility
Timing to deal with uncertain factors	After solving the problem	Before solving the problem	Before solving the problem	Before solving the problem
Description of uncertain parameters in the model	------------	Random variables with known probability distributions	Scenario sets with probabilities of occurrence	Variables with epistemic uncertainty
Optimal solution	------------	• Not the true optimal solution. • Infeasible solution is allowed.	• Not the true optimal solution. • Infeasible solution is not allowed.	• Optimal solution with an associated degree of feasibility
Characteristics	• Easy to conduct. • Gives insight of change in solution if input data is varied. • Cannot determine a suitable solution to accommodate uncertainty impact.	• Mitigates uncertainty impacts on decision by considering uncertain factor before stochastic events occur. • Difficult to solve.	• Mitigates uncertainty impacts on decision by considering uncertain factor before stochastic events occur. • Decision maker’s preference toward risk can be accounted for.	• Mitigates uncertainty impacts on decision by considering uncertain factor before stochastic events occur. • Decision maker’s preference toward risk can be accounted for.

2.5. Research Gaps

From the literature review following are the few observations with research gap:

- From the literature review of network design models in reverse logistics (Table 2.5), it is observed that in the early literature most of models are open-loop supply chain models with the objective of recycling or waste disposal. Later it was recognized that closed-loop supply chain models can provide better economical, environmental and social benefits. It is observed from the literature review of closed-loop supply chain models (Table 2.6) that most of the CLSC models are specific to an industry or a product type. From Table 2.8 - 2.11 it is further observed that different models consider different set of product recovery options, different set of reverse logistic cost and different set of binary locations and different methods to handle uncertainty in parameters. Table 2.13 highlights the salient features and research gap for some of the closed-loop supply chain models.
- It is observed that there is need to design and optimize a generalized closed-loop supply chain model that considers the different costs (like incentive to customer, processing and set-up cost at facility centers, transportation cost, profit from recycling and waste disposal cost), different product recovery options (like reuse, recycle, remanufacture and, disposal), and uncertainty in parameters (like demand of product; unit cost of collection, disassembly, refurbishing and disposal; set-up cost at each facility center; capacity of each facility center; unit purchasing cost and maximum percentage of parts that can be reused, refurbished recycled and disposed), to make the design more pragmatic.

Table 2.13: Salient features and research gap of closed-loop supply chain models

Author	**Objective (s)**	**Method to handle uncertainty**	**Uncertain parameters**	**Salient features and research gap**
Kim *et al.*(2006)	To determines the quantity of products/parts to be processed in the remanufacturing facilities and the amount of parts to be purchased from the external suppliers while maximizing the total cost saving.	Sensitivity analysis	Capacity of collection center, disassembly center and refurbish center	▪ Disassembly cost, refurbishing cost, disposal cost, set-up cost and inventory cost are considered, but the transportation cost, collection cost and incentive to customers is not considered in the model. ▪ Refurbishing and disposal is considered, but recycling, repair and reuse of products is not considered. ▪ Multiple locations for different facility centers are not considered. ▪ Multiple external suppliers are not considered for new part supply.
Lu and Bostel (2007)	To minimize the total cost while determining the location and allocation of producers, remanufacturing centers and intermediate centers.	Not considered	-------------------	▪ Fixed cost, processing cost, remanufacturing cost, shipping cost, and disposal cost are considered but the inventory cost, unit recycling cost/profit and incentive to customer are not considered. ▪ Uncertainty in parameters like demands and return from customers is assumed to be known and deterministic. ▪ Location and allocation considered only for producers, remanufacturing centers and intermediate centers.
Demirel and Gökçen (2008)	To minimize the total cost while determining the number of products to be disassembled, the number of parts to be purchased from suppliers and the location-allocation of disassembly, collection and distribution facilities.	Sensitivity analysis	Rate of return	▪ Only rate of return is the considered as uncertain parameters. ▪ Only remanufacturing and disposal is considered but repair, reuse and recycle is not considered in the model. ▪ The proposed model is single time period model and inventory cost is not considered.

Table 2.13 Salient features and research gap of closed-loop supply chain models (contd.)

Author	**Objective (s)**	**Method to handle uncertainty**	**Uncertain parameters**	**Salient features and research gap**
Mutha and Pokharel (2009)	To determine the number of facilities, their locations - allocation and the corresponding flow of used products and modules at an optimal cost.	Scenario analysis	Quantity of return, capacity of processing centers, and disposal to recycle percentage	▪ Although, the demands for remanufactured products can vary, but this current model assumes only deterministic demands by assuming historical averages. ▪ Recycle, disposal and remanufacturing is considered but the reuse of products is not considered.
Lee *et al.* (2010)	To minimize the total cost by deciding the type of facility (forward processing, collection or hybrid facility) to build at each potential depot, their location and the quantities of forward and returned products shipped in the transportation links.	Stochastic programming	Demand of forward products and supply of returned products	▪ Only fixed cost, transportation cost and processing cost at facility centers considered, but the collection cost, inventory cost, product acquisition cost, disposal cost and recycling cost not considered. ▪ Different product recovery options are not considered.
Shi *et al.*(2011)	To maximize the manufacturer's expected profit by jointly determining the production quantities of brand-new products, the quantities of remanufactured products and the acquisition prices of the used products, subject to a capacity constraint.	Sensitivity analysis	Demand and return of products	▪ Only demand and return of products assumed to be uncertain and price sensitive. ▪ The proposed model is a single time period model and inventory cost is not considered. ▪ Remanufacturing of product is considered, but the returned products are not categorized into different end-of-life processes like reuse, repair, recycle or disposal.

Table 2.13 Salient features and research gap of closed-loop supply chain models (contd.)

Author	Objective (s)	Method to handle uncertainty	Uncertain parameters	Salient features and research gap
Pishvaee *et al.* (2011)	To minimize the total cost while determining the location and transportation quantity between facility centers	Robust Optimization	Uncertainty in returned products, demands for recovered products and transportation costs	▪ Only fixed cost, shipping cost and penalty cost per unit of non-satisfied demand of customers considered. ▪ Binary variables considered only for collection, recovery and redistribution centers. ▪ Single time period model and inventory cost and incentive to customers not considered.
Özceylan and Paksoy (2012a)	To develop an integrated, multi-echelon, multi-period mixed-integer linear programming model to minimize the total cost.	Scenario analysis	Percentage of product recovery options	▪ After disassembly there can be some fraction of parts for recycling, this is not considered. ▪ Only refurbishing cost, transportation cost considered, but the processing cost at collection center, disassembly center, disposal center and recycling cost not considered. ▪ Fixed cost for plants and retailers considered, but not considered for collection centers, disassembly centers and refurbishing centers. ▪ Incentive to customers or the product acquisition cost not considered in the model.
Amin and Zhang (2012)	The objective of model is to (i) maximize profit of the organization, (ii) maximize the weights of suppliers and (iii) to minimize defect rates. The model not only determines the amount of parts and products in the nodes of CLSC network, but also selects the best suppliers and refurbishing sites.	Fuzzy numbers	Supplier selection related parameters only	▪ The cost of disassembly, refurbishing and disposal are considered but the cost of transportation, collection cost, incentive to customers and recycling profit not considered. ▪ Refurbishing and disposal considered but repair, reuse and recycling as product recovery option are not considered. ▪ Multiple locations for refurbishing centers considered. ▪ Single time horizon and inventory cost is not considered.

Table 2.13 Salient features and research gap of closed-loop supply chain models (contd.)

Author	Objective (s)	Method to handle uncertainty	Uncertain parameters	Salient features and research gap
Özceylan and Paksoy (2012b)	The objectives of the model are to (i) minimize total manufacturing and distribution costs, (ii) minimize total fixed costs of plants and retailers.	Fuzzy programming	Demand, capacity and reverse rates	▪ Three parameters, i.e. demand, capacity and reverse rates is considered uncertain and all the other parameters are taken as crisp numbers. ▪ Unit cost of processing at collection center, disassembly center, disposal center, inventory cost, and incentive to customers not considered. ▪ Recycling as a product recovery option not considered.
Pishvaee and Razmi (2012)	The objectives of the model are to (i) minimize total cost, (ii) minimize the environmental impact.	Fuzzy programming	Demand, return, fixed cost, transportation cost, processing cost, capacity at facility centers	▪ Recycling and disposal are considered as product recovery options but repair, reuse, refurbishing etc. are not considered. ▪ The refund to customer, inventory cost and disassembly cost are not taken into account.
Amin and Zhang (2013a)	To minimize the total cost of a CLSC network and maximize the effect of using environmental friendly material and using clean technology.	Scenario analysis	Demand and return volume	▪ Fixed cost for plant and collection centers only. ▪ Incentive to customers and inventory cost not considered ▪ Uncertainty in other parameters like percentage of products/parts that can be reused, refurbished, recycled and disposed not considered. ▪ Product disassembly not considered.

- Review of closed-loop supply chain models shows that most of models are single objective models with maximization of profit or minimization of cost (Table 2.6) and a few models consider multi-objective optimization (Table 2.7). With the increasing demand of sustainability, optimization with only economical objective is not sufficient, so there is a need to develop a multi-objective CLSC model that considers the environmental and social factors along with economical objective, including different costs, product recovery options and uncertainty in parameters.
- Review of the collection activities (Section 2.3.1 and Table 2.2), product recovery processes (Section 2.3.3 and Table 2.4) and network configurations in reverse logistics shows that there is a need to develop decision making models for the assessment and evaluation of collection methods, product recovery processes and network configurations in reverse logistics, considering the inherent uncertainty of reverse logistics.

CHAPTER 3

SINGLE OBJECTIVE CLOSED-LOOP SUPPLY CHAIN DESIGN AND OPTIMIZATION

Based on literature review of network design models in reverse logistics this chapter provides a multi-product, multi-echelon, capacitated closed-loop supply chain framework and a single objective optimization model considering uncertainty in parameters. The uncertainty related to demand, fraction of parts recovered, product acquisition cost, purchasing cost, transportation cost, inventory cost, processing and set-up cost is handled with fuzzy numbers. A fuzzy mixed-integer linear programming model is proposed for single-time period return, which is further extended to multi-time period return to decide optimally the location and allocation of parts at each facility center, number of products to be remanufactured and number of parts to be purchased from external suppliers in order to maximize the profit of organization. The proposed models have been tested with illustrative examples.

3.1. Introduction

In recent years closed-loop supply chain (CLSC) management has attracted the attention of researchers and manufacturers due to the revolution in green manufacturing, increased environmental concerns, government legislations, and awareness of limited natural resource (Özceylan and Paksoy, 2013a). It is an environmentally and economically sound approach to achieve many of the goals of sustainable development (Ayres *et al.*, 1997; Ferrer, 1997a; Ferrer, 1997b; Thierry *et al.*, 1995). In many industries, original equipment manufacturers (OEMs) are looking for efficient ways to integrate reverse logistics into their supply chains to recover economic value from returned products and reduce disposal costs (Autry, 2005; Realff *et al.*, 2000). As OEMs have more knowledge on products and markets, they can operate the manufacturing and remanufacturing activities together and optimize the value of the closed-loop system. Remanufacturing of used products and bringing them back to the market provides not only the environmental and customer benefits but it also reduces the production cost of OEMs (Lee *et al.*, 2009). Compared with normal production, manufacturers can save about 40-60 percent of the cost while paying for only 20 percent of the manufacturing effort (Dowlatshahi, 2000). Kim *et al.* (2008) demonstrated that a remanufactured product uses less than 20% of the materials, 16% of the energy and releases only 35% of the greenhouse gas emissions of those released in the process of producing a new product.

The production planning and network design of CLSC is a major challenge as compared to forward supply chain (Guide *et al.*, 2003; Wang and Huang, 2013). In the CLSC, the manufacturer needs to integrate both manufacturing and remanufacturing activities by using the parts recovered from return products and the new parts purchased from external suppliers. It is further complicated as the quantity, quality and timing of the return are also quite uncertain (Guide Jr, 2000; Shi *et al.*, 2011). This uncertainty affects the percentage of products/parts recovered for different product recovery options like reuse, refurbish, recycle, and disposal. The fraction of parts recovered by different recovery options being uncertain, affect the processing, and set-up cost at various facility centers. Therefore, in this uncertain environment, determining the number of products to be remanufactured, the number of parts to be directly purchased as well as the location and allocation of external supplier(s), collection center(s), disassembly center(s), refurbishing center(s), recycling center(s), and disposal center(s) is challenging to maximize the total profit. Multiple costs like refund to the customer, purchasing cost from external supplier(s), transportation cost, inventory cost, processing cost and set-up cost at each facility further complicate the closed-loop supply chain solutions. There is uncertainty involved at each output of the reverse portion of the supply chain unlike the forward portion of the supply chain. The reverse supply chain provides ill-known parameters affecting the forward portion and thus making the whole supply chain environment uncertain.

From the literature review of network design model for reverse logistics in section 2.4.2 (i.e. Table 2.8, 2.9, 2.10, 2.11) and gap analysis in section 2.5 (i.e. Table 2.13), it was observed that different models consider different set of product recovery options, different set of reverse logistic cost, different set of binary variables and different set of uncertain parameters. So, it was recognized there is need to design and optimize a generalized closed-loop supply chain model that considers the different costs (like incentive to customer, processing and set-up cost at facility centers, transportation cost, profit from recycling and waste disposal cost), different product recovery options (like reuse, recycle, refurbishing and disposal), and uncertainty in parameters (like demand of product; unit cost of collection, disassembly, refurbishing and disposal; set-up cost at each facility center; capacity of each facility center; unit purchasing cost and maximum percentage of parts that can be reused, refurbished recycled and disposed) simultaneously in the model.

Therefore, this chapter provides a multi-product, multi-echelon capacitated closed-loop supply chain framework and a single objective optimization model in an uncertain environment for single-time period returns, which is further extended to multi-time period returns with inventory flow. A fuzzy mixed-integer linear programming model is proposed to represent the proposed framework in mathematical terms to maximize the profit by optimally deciding the quantity of parts to be processed at each reverse supply chain facility and the number of parts to be purchased from multiple suppliers. It also provides optimal location and allocation to different collection centers, disassembly centers, refurbishing centers and external suppliers. The model also takes into consideration the product acquisition cost, transportation cost, collection and inspection cost, disassembly cost, refurbishing cost, disposal cost, set-up cost, and recycling profit at various facility locations. The uncertainty related to ill-known parameters (e.g. product demand, percentage of return, transportation cost, processing and set up cost, and percentage of parts recovered for reuse, disassemble, refurbish, disposal and recycle) is represented by triangular fuzzy numbers (TFNs). The advantages of mapping uncertainty with TFNs are presented in section 3.2.4.

The proposed framework is tested by solving an illustrative CLSC network problem using the methodology proposed by Jiménez *et al.* (2007). The advantage of the methodology is that, it allows working with the concept of feasibility degree to find an optimal solution between two conflicting objectives, i.e. to improve the objective function value and to improve the degree of satisfaction of constraints simultaneously. As higher the degree of satisfaction of constraints, smaller is the feasible region and consequently worst is the optimal objective value. The model is solved using LINGO 13, an optimization tool.

3.2. Method of Handling Uncertainty

The dynamic and imprecise nature of quantity and quality of end-of-life (EOL) products imposes a high degree of uncertainty in reverse and closed-loop supply chain network design decisions (Pishvaee and Razmi, 2012). Literature suggests different types of uncertainties and different methods to handle them. Dubois *et al.* (2003) has discussed that uncertainty can be due to: (i) flexibility in constrain/target value, (ii) uncertainty in data. Uncertainty in data can be further classified in two types, i.e. uncertainty due to randomness in data and uncertainty due to ill-known parameters (known as epistemic uncertainty).

Literature also suggests different methods to handle uncertainty like stochastic programming, fuzzy mathematics, robust optimization, etc. Some of the literature applied stochastic programming approaches to cope with this problem (El-Sayed *et al.*, 2010; Listeş, 2007; Pishvaee *et al.*, 2009). However, the need of sufficient historical data that is rarely available in real-life cases and the high computational complexity are major drawbacks that make the use of stochastic programming models somehow difficult in real cases (Pishvaee and Razmi, 2012). Thus, a few number of works in recent years used more flexible approach such as fuzzy programming to handle the uncertainty (Kannan *et al.*, 2013; Özceylan and Paksoy, 2013b; Özceylan and Paksoy, 2014).

The type of uncertainty due to ill-known parameters is usually modeled by fuzzy numbers in the setting of possibility theory (Mula *et al.*, 2010; Mula *et al.*, 2006; Peidro *et al.*, 2009; Pishvaee and Torabi, 2010). The type of uncertainty in the present case is also due to ill-known parameters and is mapped with triangular fuzzy numbers. The next section provides the basics of fuzzy sets.

3.2.1. Overview of fuzzy sets

This section provides some basic concepts of fuzzy sets and linguistics variables. In order to deal with vagueness of human thought, Zadeh (1965) first introduced the fuzzy set theory. A fuzzy set is a class of objects with a continuum of grades of membership. Such a set is characterized by a membership function which assigns to each object a grade of membership ranging between zero and one (Zadeh, 1965). Fuzzy sets and fuzzy logic are powerful mathematical tools for modeling uncertain systems in industry, nature and humanity; and facilitators for common-sense reasoning in decision-making in the absence of complete and precise information (Ertuğrul and Karakaşoğlu, 2008). Fuzzy sets theory providing a wider frame than classic sets theory in reflecting the real world

(Ertuğrul and Tuş, 2007). Modeling using fuzzy sets has proven to be an effective way for formulating decision problems where the information available is subjective and imprecise (Zimmermann, 2001).

3.2.2. Linguistic variable

A linguistic variable is a variable whose values are words or sentences in a natural or artificial language (Zadeh, 1975). As an illustration, height is a linguistic variable if its values are assumed to be the fuzzy variables labeled short, medium, high etc. rather than the numbers 0, 1, 2,.. (Bellman and Zadeh, 1977). It provides a means of approximate characterization of the phenomena which are too complex or too ill-defined to be amenable to description in conventional quantitative terms. Linguistic variable have been found intuitively easy to use in expressing the subjective and/or qualitative imprecision of a decision maker's assessment. The main applications of the linguistic approach lie in the realm of humanistic systems-especially in the fields of artificial intelligence, linguistics, human decision processes, psychology, law, information retrieval, economics and related areas (Zadeh, 1975).

3.2.3. Defining fuzzy number

A fuzzy number is a special fuzzy set $F = \{(x, \mu_F(x)), x \in R\}$, where x takes it values on the real line, R: $-\infty < x < +\infty$ and $\mu_F(x)$ is a continuous mapping from R to the closed interval [0, 1]. It is possible to use different pattern of fuzzy numbers like, triangular, trapezoidal, etc. But the most commonly used is triangular pattern, because of some advantages that will be discussed next.

The decision makers can construct the triangular distribution based on the three prominent data: (i) the most pessimistic value that has a very low likelihood of belonging to the set of available values (membership degree = 0 if normalized); (ii) the most possible value that definitely belongs to the set of available values (membership degree = 1 if normalized); and (iii) the most optimistic value that has a very low likelihood of belonging to the set of available values (membership degree = 0 if normalized).

Therefore a triangular fuzzy number can be represented as $\tilde{M} = (l, m, u)$, where $l \leq m \leq u$, has the following triangular type membership function (Figure 3.1);

$$\mu_F(x) = \begin{cases} 0 & x < l \\ (x-l)/(m-l) & l \leq x \leq m \\ (u-x)/(u-m) & m \leq x \leq u \\ 0 & x > u \end{cases}$$

Alternatively, by defining the confidence level α, the triangular fuzzy number can be characterized as:

$$\tilde{M}_\alpha = [l^\alpha, u^\alpha] = [l + (m-l)\alpha, u - (u-m)\alpha] \quad \forall \alpha \in [0,1]$$

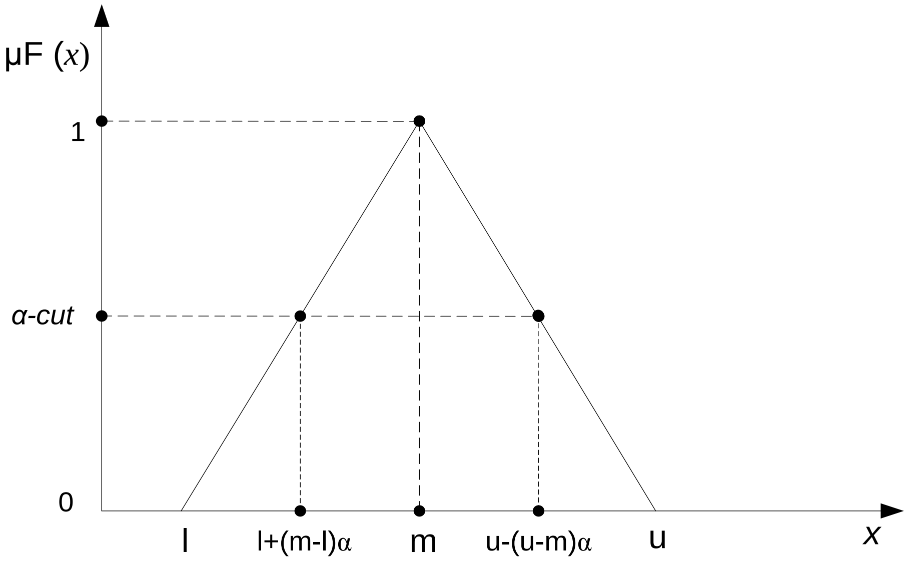

Figure 3.1: Triangular fuzzy number and α-cut

There are various operations on triangular fuzzy numbers. Few of the important operations are illustrated here. If $\tilde{M}_1$ and $\tilde{M}_2$ are two positive triangular fuzzy numbers defined by (l_1, m_1, u_1) and (l_2, m_2, u_2) then:

$$\tilde{M}_1 \pm \tilde{M}_2 = (l_1 \pm l_2, \quad m_1 \pm m_2, \quad u_1 \pm u_2)$$

$$\tilde{M}_1 \otimes \tilde{M}_2 = (l_1 \times l_2, \quad m_1 \times m_2, \quad u_1 \times u_2)$$

$$(\tilde{M}_1)^{-1} \approx (1/u_1, \quad 1/m_1, \quad 1/l_1)$$

$k * (\tilde{M}_1) = (k * l_1, \quad k * m_1, \quad k * n_1)$, where k is a positive real number

3.2.4. Advantages of triangular fuzzy numbers

A fuzzy number can be represented by different distributions like triangular, trapezoidal, etc. Yang *et al.* (1991) recommended employing triangular distribution when the mode (most likely value) and range (limit of optimistic and pessimistic values) of a fuzzy number are known. Triangular is the most common used distribution because of the following advantages.

- The primary advantages of the triangular fuzzy number are the simplicity and flexibility of the fuzzy arithmetic operations (Wang and Liang, 2005)
- The pattern of triangular distribution is commonly adopted due to ease in defining the maximum and minimum limit of deviation of the fuzzy number from its central value, as the decision makers are familiar with estimating optimistic, pessimistic and most likely parameters (Liang, 2008).
- When knowledge of the decision maker is limited, triangular distribution is appropriate for representing a fuzzy number (Rommelfanger, 1996).

3.3. The Proposed Single Period CLSC Network and Mathematical Model

3.3.1 Description of the proposed single period CLSC network

A generalized single period CLSC network is presented for handling multi-product returns in which forward flow, reverse flow and their mutual interactions are considered simultaneously. The network (Figure 3.2) is structured as a typical five-echelon forward supply chain consisting of raw-material suppliers, plants, distributors, retailers, and customers. The reverse supply chain is also five-echelon including collection/repair centers, disassembly centers, refurbishing centers, recycling centers, and disposal centers as shown in Figure 3.2.

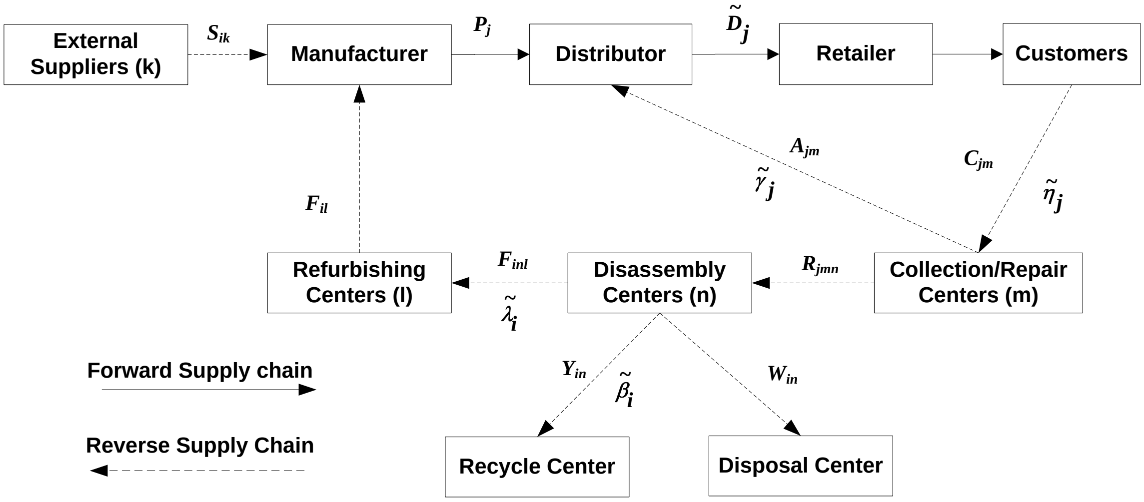

Figure 3.2: The proposed single period closed-loop supply chain framework

Product recovery system starts with the collection of returned products from the customers with some incentive to them. It is assumed that $\tilde{\eta}_j$ is the maximum percentage of products collected from the customers. At the collection facility center inspection, sorting and repair is done. The products which can be reused after minor repair or cleaning are sent to distribution center and the rest are forwarded for disassembly. It is further assumed that $\tilde{\gamma}_j$ is the maximum percent age of collected products that are reused and the rest are sent for disassembly. Since a product consists of various parts, the returned products are disassembled to remanufacture the parts. Disassembled parts are classified into the refurbishable parts, recyclable parts and disposable parts. It is assumed that out of the disassembled parts, $\tilde{\lambda}_i$ is the maximum percentage of parts that will go to the refurbishing center, $\tilde{\beta}_i$ is the maximum percentage of parts that will go to recycling center and the rest of parts will be disposed off. After refurbishing process, the refurbished parts and the new parts purchased from the external supplier(s) are supplied to the manufacturing plant according to the production plan.

Assumptions in the framework

The following are the assumptions in the proposed CLSC framework:

(i) The remanufactured products have same quality as the brand-new products and can be sold in the same market with the same price (Beamon and Fernandes, 2004; Kim *et al.*, 2006).

(ii) Inventory costs are not considered in model as the storing period for parts is assumed negligible (Amin and Zhang, 2013; Harraz and Galal, 2011).

(iii) Only parts of products can be disposed off or recycled and not the whole product (Harraz and Galal, 2011).

(iv) The recycleable parts are given to the recycler for a profit (Harraz and Galal, 2011).

The company is interested in minimizing total cost so that eventually it can maximize total profit. The framework contains multiple collection centers, disassembly centers, and refurbishing centers and allocates optimal number of products/parts to be processed at these facility centers. Similarly, it allocates optimally the number of parts to be purchased from different external suppliers. The model considers multi-product with different reuse, refurbish, disposal and recycling fractions. Collection, disassembly, and refurbishing centers have limited capacities in the proposed model. The recyclable parts are given to the recycler for a profit.

The product demand; cost parameters; and fraction of parts recovered for reuse, refurbish, recycle, and disposal are affected by the uncertainty in quantity, quality and time of return. So assigning a crisp value to parameters in the model is very difficult for the experts/decision makers. As discussed in section 3. 2, the type of uncertainty in the present case is of ill-known parameters and therefore these uncertain parameters are modeled by fuzzy numbers (Mitra, 2012; Pishvaee and Razmi, 2012). The proposed framework is expected to represent a more realistic CLSC situation.

3.3.2 The proposed fuzzy mixed-integer linear programming model

The proposed Fuzzy Mixed-Integer Linear Programming (Fuzzy MILP) model is presented in this section. The Fuzzy MILP model represents the proposed framework in mathematical terms for optimization of the total profit of the organization.

Indices

j	set of products, j = 1, 2,…..J
i	set of parts, i = 1, 2,…..I
k	set of suppliers, k = 1, 2,…..K
m	set of collection/repair centers, m = 1, 2,…..M
n	set of disassembly centers, n = 1, 2,…..N
l	set of refurbishing centers, l = 1, 2,…..L

Decision variables

P_j	units of product j to be produced
C_{jm}	units of product j to be collected at collection center m
A_{jm}	units of product j to be reused from collection center m
R_{jmn}	units of product j to be disassembled at site n from collection center m
R_{jn}	units of product j to be disassembled at site n
S_{ik}	units of part i to be purchased from supplier k
T_{in}	units of part i to be disassembled at disassembly site n
F_{inl}	units of parts i to be refurbished at site l from disassembly center n
F_{il}	units of part i to be refurbished at refurbishing center l
W_{in}	units of part i to be disposed off from disassembly center n

Y_{in}	units of part *i* to be recycled from disassembly center *n*
B_{jm}	binary variable for set-up of collection facility for product *j* at *m*
V_{jn}	binary variable for set-up of disassembly site for product *j* at *n*
U_{il}	binary variable for set-up of refurbishing site for part *i* at *l*

Parameters

$\tilde{D}_j$	demand of product *j* to be produced
q_{ij}	units of part *i* in product *j*
$(MP)_j$	maximum capacity of product *j* to be produced by the plant
$(C\tilde{C})_{jm}$	unit cost of collection and inspection for product *j* at collection center *m*
$(S\tilde{C})_{jm}$	set-up cost for collection of product *j* at center *m*
$(M\tilde{C})_{jm}$	maximum capacity of the collection center *m* for product *j*
$(D\tilde{C})_{in}$	unit cost of disassembly for part *i* at disassembly center *n*
$(S\tilde{D})_{jn}$	unit set-up cost for disassembly of product *j* at center *n*
$(M\tilde{D})_{jn}$	maximum capacity of the disassembly center *n* for product *j*
$(R\tilde{C})_{il}$	unit cost of refurbishing for part *i* at center *l*
$(S\tilde{R})_{il}$	unit set-up cost for refurbishing of part *i* at center *l*
$(M\tilde{R})_{il}$	maximum capacity of the refurbishing center *l* for part *i*
$(U\tilde{C})_{jm}$	unit cost of repair for product *j* from collection center *m*
$(W\tilde{D}C)_i$	unit cost of disposal for part *i*
$(P\tilde{F})_j$	unit profit from product *j*
$(R\tilde{P})_i$	unit profit of recycling for part *i*
$(R\tilde{F})_{jm}$	unit cost of refund to customers for product *j*
$(P\tilde{C})_{ik}$	unit purchasing cost for part *i* from supplier *k*
$(MXS)_k, (MNS)_k$	maximum and minimum purchase order from supplier *k*
$(T\tilde{C}D)_{jmn}$	unit cost of transportation from collection center *m* to disassembly center *n* for product *j*

$(\widetilde{TCR})_{inl}$	unit cost of transportation from disassembly center n to refurbishing center l for part i
$(\widetilde{TCU})_{jm}$	unit cost of transportation from collection/repair center m to distributor for product j
$\tilde{\eta}_j$	maximum percentage of product j returned
$\tilde{\gamma}_j$	maximum percentage of product j reused
$\tilde{\lambda}_i$	maximum percentage of part i refurbished
$\tilde{\beta}_i$	maximum percentage of part i recycled

It should be noted that symbols with a tilde (~) at the top indicated the parameters with uncertainty and are estimated by appropriate possibility distribution.

Objective function

Maximize

$$\begin{aligned}
&\sum_j (\widetilde{PF}_j) * (P_j + \sum_m A_{jm}) + \sum_n \sum_i (\widetilde{RP})_i * Y_{in} - \sum_k \sum_i (\widetilde{PC})_{ik} * S_{ik} - \sum_m \sum_j (\widetilde{CC})_{jm} * C_{jm} \\
&- \sum_m \sum_j (\widetilde{SC})_{jm} * B_{jm} - \sum_m \sum_j (\widetilde{UC})_{jm} * A_{jm} - \sum_n \sum_i (\widetilde{DC})_{in} * T_{in} - \sum_n \sum_j (\widetilde{SD})_{jn} * V_{jn} \qquad (3.1) \\
&- \sum_l \sum_i (\widetilde{RC})_{il} * F_{il} - \sum_l \sum_i (\widetilde{SR})_{il} * U_{il} - \sum_n \sum_i (\widetilde{WDC})_i * W_{in} - \sum_j \sum_m (\widetilde{RF})_{jm} * C_{jm} \\
&- \sum_j \sum_m \sum_n (\widetilde{TCD})_{jmn} * R_{jmn} - \sum_i \sum_n \sum_l (\widetilde{TCR})_{inl} * F_{inl} - \sum_j \sum_m (\widetilde{TCU})_{jm} * A_{jm}
\end{aligned}$$

The objective function (Equation 3.1) is to maximize the total profit of the organization. The first two terms of the objective function reflect the profit earned by selling the products and profit from recyclers respectively. The third term represents the purchasing cost of parts from external suppliers. The fourth and fifth terms represent the processing and set-up cost at collection centers. Cost of repair for the reused products is represented by sixth term. The seventh and eighth term represents the processing and set-up cost at the disassembly centers. The next two terms represent the processing and set-up cost at refurbishing centers. The 11th and 12th terms represent the waste disposal cost and cost of product acquisition (refund given to customers) respectively. The last three terms represents the transportation cost of retuned products from collection to disassembly centers, transportation cost of refurbishable parts from disassembly centers to refurbishing centers, and transportation cost of reused products from collection/repair centers to distributor centers respectively.

Subject to

Demand constraint

Constraint (3.2) ensures that demand for each product is satisfied with the sum of newly produced products and reused products.

$$\tilde{D}_j = P_j + \sum_m A_{jm} \qquad \forall j \tag{3.2}$$

Flow balance constraints

Constraint (3.3) ensures that number of products collected at collection centers is equal to sum of number of products reused and number of products disassembled. Similarly constraint (3.4) ensures the flow balance at disassembly center, i.e. number of parts disassembled is equal to sum of parts refurbished, recycled, and disposed off. Constraint (3.5) ensures that the total requirement of parts is equal to sum of parts refurbished and parts purchased from external supplier(s). Constraint (3.6), (3.7) and (3.8) calculate the number of parts at disassembly centers, number of parts at refurbishing centers and number of products at disassembly centers respectively.

$$C_{jm} = A_{jm} + \sum_n R_{jmn} \qquad \forall j, m \tag{3.3}$$

$$T_{in} = Y_{in} + W_{in} + \sum_l F_{inl} \qquad \forall i, n \tag{3.4}$$

$$\sum_j q_{ij} * P_j = \sum_l F_{il} + \sum_k S_{ik} \qquad \forall i \tag{3.5}$$

$$T_{in} = \sum_m \sum_j q_{ij} R_{jmn} \qquad \forall i, n \tag{3.6}$$

$$F_{il} = \sum_{n} F_{inl} \qquad \forall i,l \tag{3.7}$$

$$R_{jn} = \sum_{m} R_{jmn} \qquad \forall j,n \tag{3.8}$$

Capacity constraints

Constraints (3.9), (3.10), (3.11), and (3.12) provide the maximum limit on the number of products collected, number of products reused, number of parts refurbished and number of parts to be recycled respectively. Constraints (3.13), (3.14) and (3.15) ensure the capacity limit for collection center, disassembly center and refurbishing center respectively. Constraint (3.16) ensures the maximum and minimum capacity of the external suppliers. The number of products to be produced is less than the plant capacity is ensured by constraint (3.17).

$$\sum_{m} C_{jm} \le \tilde{\eta}_j * \tilde{D}_j \qquad \forall j \tag{3.9}$$

$$A_{jm} \le \tilde{\gamma}_j * C_{jm} \qquad \forall j,m \tag{3.10}$$

$$\sum_{l} F_{inl} \le \tilde{\lambda}_i * T_{in} \qquad \forall i,n \tag{3.11}$$

$$Y_{in} \le \tilde{\beta}_i * T_{in} \qquad \forall i,n \tag{3.12}$$

$$C_{jm} \le (MC)_{jm} * B_{jm} \qquad \forall j,m \tag{3.13}$$

$$\sum_{m} R_{jmn} \le (MD)_{jn} * V_{jn} \qquad \forall j,n \tag{3.14}$$

$$\sum_{n} F_{inl} \le (MR)_{il} * U_{il} \qquad \forall i,l \tag{3.15}$$

$$(MNS)_k \le \sum_{i} S_{ik} \le (MXS)_k \qquad \forall k \tag{3.16}$$

$$P_j \le (MP)_j \qquad \forall j \tag{3.17}$$

Decision variable constraints

The following constraints (3.18, 3.19) are related to binary and general integer values of the decision variables. All the decision variables are positive numbers.

$$B_{jm}, V_{jn}, U_{il} \quad \in \{0,1\} \qquad \forall i, j, m, n, l \tag{3.18}$$

$$P_j, C_j, A_{jm}, R_{jmn}, R_{jn}, S_{ik}, T_{in}, F_{inl}, F_{il}, W_{in}, Y_{in} \quad \in I \qquad \forall i, j, m, n, l, k \tag{3.19}$$

3.4. The Proposed Solution Methodology

The uncertainties in the proposed model are handled using possibilistic programming approach. The possibility distribution represents the degree of occurrence of values for each uncertain parameter and is determined based on available data as well as expert knowledge. Each ill-known parameter is represented with a triangular fuzzy number. The pattern of triangular distribution is commonly adopted to handle ill-known parameters as the decision makers are familiar with estimating the optimistic, pessimistic and most likely value of the ill-known parameters (Liang, 2008; Yang *et al.*, 1991). Rommelfanger (1996) also recommended triangular distribution of the fuzzy number when knowledge of the decision maker is limited. The triangular shape also provides the simplicity and flexibility of the fuzzy arithmetic operations (Liang, 2006). The fuzzy input provided by the experts is next converted into crisp values.

3.4.1 Converting the fuzzy MILP model into crisp MILP model

A number of methods are proposed in the literature to deal with possibilistic programming models (Jiménez *et al.*, 2007; Lai and Hwang, 1992; Liang, 2006). Among these methods the Jiménez *et al.* (2007) method is selected to cope with proposed fuzzy MILP model. The advantage of this method is that it allows the decision makers (DMs) to work with the concept of degree of feasibility (α). This helps the DMs to find a balanced solution between two conflicting objectives, i.e. to improve the objective function value and to improve the degree of satisfaction of constraints. As higher the degree of satisfaction of constraints, the feasible solution set becomes smaller and consequently the objective optimal value is worse. Jiménez *et al.* (2007) proposed an interactive method in order to evaluate these two conflicting factors. Also, this method is computationally efficient to solve fuzzy linear problems as it can preserve its linearity and does not increase the number of objective functions and inequality constraints. Zadeh (1975) recommended that the best way to reflect DM preferences is to express them through natural language, establishing a semantic correspondence for the different degrees of feasibility (α) such that $0 \le \alpha \le 1$. The number of elements on the semantic scale depends on the number of linguistic labels that the DM is able to distinguish. Kaufmann and Gil Aluja (1992) proposed eleven levels which allow sufficient distinction among them:

$\alpha = 0$: unacceptable solution
$\alpha = 0.1$: practically unacceptable solution
$\alpha = 0.2$: almost unacceptable solution
$\alpha = 0.3$: very unacceptable solution
$\alpha = 0.4$: quite unacceptable solutions
$\alpha = 0.5$: neither acceptable nor unacceptable solution
$\alpha = 0.6$: quite acceptable solution
$\alpha = 0.7$: very acceptable solution
$\alpha = 0.8$: almost acceptable solution
$\alpha = 0.9$: practically acceptable
$\alpha = 1$: completely acceptable solution

Depending on the wish of DM other scales can also be used. In this paper the scale mentioned above is used with the minimum acceptable degree of 0.4. As infinite number of values of degree of feasibility is not considered, the conversion of fuzzy MILP to crisp MILP is not an exact method. The numbers with superscript *pes* represents the pessimistic value of the fuzzy number, *opt* represents the optimistic value of the fuzzy number and *mos* represents the most likely value of the fuzzy number.

Crisp MILP of single period fuzzy MILP model

The equivalent crisp model of single period CLSC model is presented below.

Maximize

$$
\begin{aligned}
&\sum_{j}\left(\frac{PF_{j}^{pes}+2\times PF_{j}^{mos}+PF_{j}^{opt}}{4}\right)*(P_{j}+\sum_{m}A_{jm})+\sum_{n}\sum_{i}\left(\frac{RP_{i}^{pes}+2\times RP_{i}^{mos}+RP_{i}^{opt}}{4}\right)*Y_{in}\\
&-\sum_{k}\sum_{i}\left(\frac{PC_{ik}^{pes}+2\times PC_{ik}^{mos}+PC_{ik}^{opt}}{4}\right)*S_{ik}-\sum_{m}\sum_{j}\left(\frac{CC_{jm}^{pes}+2\times CC_{jm}^{mos}+CC_{jm}^{opt}}{4}\right)*C_{jm}\\
&-\sum_{m}\sum_{j}\left(\frac{SC_{jm}^{pes}+2\times SC_{jm}^{mos}+SC_{jm}^{opt}}{4}\right)*B_{jm}-\sum_{m}\sum_{j}\left(\frac{UC_{jm}^{pes}+2\times UC_{jm}^{mos}+UC_{jm}^{opt}}{4}\right)*A_{jm}\\
&-\sum_{n}\sum_{i}\left(\frac{DC_{in}^{pes}+2\times DC_{in}^{mos}+DC_{in}^{opt}}{4}\right)*T_{in}-\sum_{n}\sum_{j}\left(\frac{SD_{jn}^{pes}+2\times SD_{jn}^{mos}+SD_{jn}^{opt}}{4}\right)*V_{jn}\\
&-\sum_{l}\sum_{i}\left(\frac{RC_{il}^{pes}+2\times RC_{il}^{mos}+RC_{il}^{opt}}{4}\right)*F_{il}-\sum_{l}\sum_{i}\left(\frac{SR_{il}^{pes}+2\times SR_{il}^{mos}+SR_{il}^{opt}}{4}\right)*U_{il}\\
&-\sum_{n}\sum_{i}\left(\frac{WDC_{i}^{pes}+2\times WDC_{i}^{mos}+WDC_{i}^{opt}}{4}\right)*W_{in}-\sum_{j}\sum_{m}\left(\frac{RF_{jm}^{pes}+2\times RF_{jm}^{mos}+RF_{jm}^{opt}}{4}\right)*C_{jm}\\
&-\sum_{j}\sum_{m}\sum_{n}\left(\frac{TCD_{jmn}^{pes}+2\times TCD_{jmn}^{mos}+TCD_{jmn}^{opt}}{4}\right)*R_{jmn}-\sum_{i}\sum_{n}\sum_{l}\left(\frac{TCR_{inl}^{pes}+2\times TCR_{inl}^{mos}+TCR_{inl}^{opt}}{4}\right)*F_{inl}\\
&-\sum_{j}\sum_{m}\left(\frac{TCU_{jm}^{pes}+2\times TCU_{jm}^{mos}+TCU_{jm}^{opt}}{4}\right)*A_{jm}
\end{aligned}
$$

And the crisp equivalents of constraint number (3.2, 3.9, 3.10, 3.11, and 3.12) are as follows:

$$
\left(\frac{D_{j}^{pes}+2\times D_{j}^{mos}+D_{j}^{opt}}{4}\right)=P_{j}+\sum_{m}A_{jm}\qquad\forall j
$$

$$
\sum_{m}C_{jm}\leq\left[\alpha\left(\frac{\eta_{j}^{pes}+\eta_{j}^{mos}}{2}\right)+(1-\alpha)\left(\frac{\eta_{j}^{opt}+\eta_{j}^{mos}}{2}\right)\right]*\left[\alpha\left(\frac{D_{j}^{pes}+D_{j}^{mos}}{2}\right)+(1-\alpha)\left(\frac{D_{j}^{opt}+D_{j}^{mos}}{2}\right)\right]\qquad\forall j
$$

$$
A_{jm}\leq\left[\alpha\left(\frac{\gamma_{j}^{pes}+\gamma_{j}^{mos}}{2}\right)+(1-\alpha)\left(\frac{\gamma_{j}^{opt}+\gamma_{j}^{mos}}{2}\right)\right]*C_{jm}\qquad\forall j,m
$$

$$
\sum_{l}F_{inl}\leq\left[\alpha\left(\frac{\lambda_{i}^{pes}+\lambda_{i}^{mos}}{2}\right)+(1-\alpha)\left(\frac{\lambda_{i}^{opt}+\lambda_{i}^{mos}}{2}\right)\right]*T_{in}\qquad\forall i,n
$$

$$Y_{in} \leq \left[\alpha \left(\frac{\beta_i^{pes} + \beta_i^{mos}}{2} \right) + (1-\alpha) \left(\frac{\beta_i^{opt} + \beta_i^{mos}}{2} \right) \right] * T_{in} \qquad \forall i, n$$

The other constraints remain as such.

3.4.2 Calculating the decision vector complying the expectations of decision maker

In order to get a decision vector that complies with the expectations of the decision maker (DM), two conflicting factors (the feasibility degree and the reaching to an acceptable value of the objective function) are evaluated. Therefore, the model is solved for each value of degree of feasibility (α) to obtain a set of acceptable solution $\tilde{z}(\alpha)$. After seeing the information given by the different $\tilde{z}(\alpha)$, the DM is asked to specify a goal such that DM is fully satisfied ($\mu_{\tilde{G}}(z)$=1) when $z \geq \overline{G}$ and DM is fully dissatisfied ($\mu_{\tilde{G}}(z)$= 0) when $z \leq \underline{G}$ as shown in Figure (3.3). For the values of *z* in between $\underline{G}$ and $\overline{G}$, $\mu_{\tilde{G}}(z)$ is approximated by linear interpolation given by equation 3.20.

$$\mu_{\tilde{G}}(z) = \begin{cases} 1 & if \quad z \geq \overline{G} \\ \left[\dfrac{z - \underline{G}}{\overline{G} - \underline{G}} \right] & if \quad \overline{G} < z < \underline{G} \\ 0 & if \quad z \leq \underline{G} \end{cases} \tag{3.20}$$

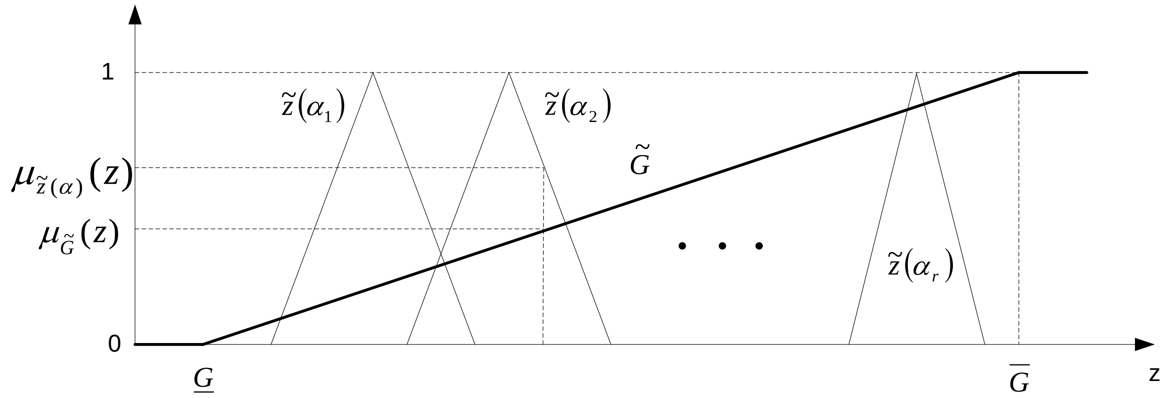

Figure 3.3: Possibility distribution of objective values and the fuzzy goal provided by decision maker

3.4.3 Computing the optimum solution

The next step is to compute the degree of satisfaction of the fuzzy goal $\tilde{G}$ for each α-acceptable solution, i.e. the membership degree of each fuzzy number $\tilde{z}(\alpha)$ to the fuzzy set $\tilde{G}$. The index proposed by Yager (1978), is used here as shown in equation (3.21).

$$K_{\tilde{G}}(z(\alpha)) = \frac{\int_{-\infty}^{+\infty} \mu_{\tilde{z}(\alpha)}(z).\mu_{\tilde{G}}(z)dz}{\int_{-\infty}^{+\infty} \mu_{\tilde{z}(\alpha)}(z)dz} \tag{3.21}$$

Where, the denominator is the area under $\mu_{\tilde{z}(\alpha)}$ and the numerator is the possibility of occurrence of $\mu_{\tilde{z}(\alpha)}(z)$ of each crisp value *z* weighted by its satisfaction degree $\mu_{\tilde{G}}(z)$ of the goal $\tilde{G}$ as shown in Figure 3.3. Now to find the balance solution between the feasibility degree and the degree of satisfaction, the membership degree of each α – acceptable optimal solution is calculated using t-norm algebraic product (equation 3.22).

$$\mu_{\tilde{D}}(x^*) = \max\left\{ \alpha * K_{\tilde{G}}(\tilde{z}(\alpha)) \right\} \tag{3.22}$$

And the best solution is one which has the greatest membership degree.

3.5. An Illustrative Example for Single Period CLSC Model

In this section a numerical example is presented to illustrate how the proposed model works in a multi-product, multi-facility CLSC framework. A data set is prepared reflecting the real business situation. It is assumed that there are two types of products and each having three types of parts with different utilization factor as shown in Table (3.1). In the network it is assumed that there are three collection/repair centers, two disassembly centers, two refurbishing centers, three external suppliers, one recycle center, and one disposal center. The processing cost, set-up cost, and maximum capacity of the collection centers, disassembly centers, and refurbishing centers are given in the

Tables 3.2, 3.3, 3.4, 3.5 respectively. The transportation cost from collection centers, disassembly centers and refurbishing centers is given in Tables 3.6, 3.7, 3.8 respectively. The other product and part related parameters including the cost of purchasing from external supplier are shown in Tables 3.9 and 3.10. The maximum purchase order for each supplier is 4000, 5000 and 5000, and the minimum purchase order for each supplier is 100. It is further assumed that $\tilde{\eta}_j$ (maximum percentage of product *j* returned) = (0.5, 0.6, 0.7), $\tilde{\gamma}_j$ (maximum percentage of product *j* reused) = (0.1, 0.2, 0.3), $\tilde{\lambda}_i$ (maximum percentage of part *i* refurbished) = (0.65, 0.7, 0.75), and $\tilde{\beta}_i$ (maximum percentage of part *i* recycled) = (0.1, 0.15, 0.2).

Table 3.1: The usage of part *i* per unit of product *j*

q_{ij}	*i*=1	*i*=2	*i*=3
j=1	2	3	2
j=2	3	3	2

Table 3.2: The collection cost, set-up cost, and maximum capacity at collection center *m* for each product *j*

Collection center	**Collection cost (CC_{jm})**			**Set-up cost (SC_{jm})**			**Maximum capacity (MC_{jm})**		
	m = 1	*m* = 2	*m* = 3	*m* = 1	*m* = 2	*m* = 3	*m* = 1	*m* = 2	*m* = 3
j = 1	(2,3,4)	(4,5,6)	(2,3,4)	(3,4,5)	(5,6,7)	(4,5,6)	300	400	300
j = 2	(3,4,5)	(3,4,5)	(4,5,6)	(4,5,6)	(3,4,5)	(4,5,6)	350	300	300

Table 3.3: The set-up cost and maximum capacity at disassembly center *n* for each product *j*

Disassembly center	**Set-up cost (SD_{jn})**		**Maximum capacity (MD_{jn})**	
	n = 1	*n* = 2	*n* = 1	*n* = 2
j = 1	(3,4,5)	(4,5,6)	500	500
j = 2	(5,6,7)	(3,4,5)	500	400

Table 3.4: The processing cost at disassembly center *n* for each part *i*

Disassembly center	**Processing cost (DC_{in})**	
	***n*=1**	***n*=2**
$i = 1$	(3,4,5)	(2,3,4)
$i = 2$	(4,5,6)	(3,4,5)
$i = 3$	(5,6,7)	(4,5,6)

Table 3.5: The processing cost, set-up cost, and maximum capacity at refurbishing center *l* for each part *i*

Refurbishing center	**Processing cost (RC_{il})**		***Set-up cost*** **(SR_{il})**		***Maximum capacity*** **(MR_{il})**	
	$l = 1$	$l = 2$	$l = 1$	$l = 2$	$l = 1$	$l = 2$
$i = 1$	(3,4,5)	(4,5,6)	(2,3,4)	(3,4,5)	1500	1800
$i = 2$	(5,6,7)	(3,4,5)	(4,5,6)	(2,3,4)	2000	1800
$i = 3$	(4,5,6)	(2,3,4)	(3,4,5)	(4,5,6)	1500	1000

Table 3.6: The transportation cost from collection center *m* to disassembly center n, for each product *j*

	TCD_{jmn} (*j*=1)			**TCD_{jmn} (*j*=2)**		
	$m = 1$	$m = 2$	$m = 3$	$m = 1$	$m = 2$	$m = 3$
$n = 1$	(0.4,0.5,0.6)	(0.3,0.4,0.5)	(0.5,0.6,0.7)	(0.3,0.4,0.5)	(0.5,0.6,0.7)	(0.3,0.4,0.5)
$n = 2$	(0.6,0.7,0.8)	(0.2,0.3,0.4)	(0.7,0.8,0.9)	(0.5,0.6,0.7)	(0.4,0.5,0.6)	(0.4,0.5,0.6)

Table 3.7: The transportation cost from disassembly center *n* to refurbishing center *l*, for each part *i*

	TCR_{inl} (*i*=1)		**TCR_{inl} (*i*=2)**		**TCR_{inl} (*i*=3)**	
	$n = 1$	$n = 2$	$n = 1$	$n = 2$	$n = 1$	$n = 2$
$l = 1$	(0.2,0.3,0.4)	(0.3,0.4,0.5)	(0.3,0.4,0.5)	(0.4,0.5,0.6)	(0.6,0.7,0.8)	(0.3,0.4,0.5)
$l = 2$	(0.1,0.2,0.3)	(0.5,0.6,0.7)	(0.2,0.3,0.4)	(0.3,0.4,0.5)	(0.2,0.3,0.4)	(0.5,0.6,0.7)

Table 3.8: The transportation cost from collection/repair center *m* to distributor center *j*

TCU_{jm}	***m*=1**	***m*=2**	***m*=3**
j=1	(0.5,0.6,0.7)	(0.3,0.4,0.5)	(0.5,0.6,0.7)
j=2	(0.7,0.8,0.9)	(0.5,0.6,0.7)	(0.7,0.8,0.9)

Table 3.9: Product related parameters

	Demand(D_j)	**Profit(PF_j)**	**Max production capacity(MP_j)**	**Refund (RF_{jm})**		
				m = 1	m = 2	m = 3
j = 1	(1400,1500,1600)	(190,200,210)	1700	(13,14,15)	(16,18,20)	(18,20,22)
j = 2	(1300,1400,1500)	(240,250,260)	1500	(18,20,22)	(13,15,17)	(16,18,20)

Table 3.10: Part related parameters

	WDC_i (waste disposal cost for part *i*)	**RP_i (recycling profit from part *i*)**	**PC_{ik} (cost of purchasing part *i* from supplier *k*)**		
			k = 1	k = 2	k = 3
i = 1	(3,4,5)	(4,5,6)	(14,16,18)	(16,18,20)	(17,19,21)
i = 2	(4,5,6)	(3,4,5)	(19,21,23)	(20,22,24)	(18,20,22)
i = 3	(2,3,4)	(5,6,7)	(20,22,24)	(19,21,23)	(21,23,25)

The proposed model is solved using LINGO 13 on intel core i5 processor machine in 0.01 second. The model contains total variables = 94, integers = 66, constraints = 81, and total non-zeros = 576. The optimum value of objective function depends on the degree of feasibility of constraints, i.e. higher the degrees of feasibility lower the value of objective function. Therefore, to find the optimum value of degree of feasibility, all the α-acceptable optimal solutions are calculated (with the minimum α = 0.4, as specified by the decision maker) as shown in Table 3.11.

Table 3.11: α-acceptable optimal solutions

Feasibility degree, α	**Possibility distribution of the objective value, $\tilde{z}(\alpha)$**
α = 0.4	(323166.3, 311963.0, 295524.9)
α = 0.5	(319127.6, 307633.8, 290740.0)
α = 0.6	(314954.2, 303152.4, 285791.4)
α = 0.7	(310834.5, 298775.0, 281012.9)
α = 0.8	(306473.6, 294148.9, 275930.6)
α = 0.9	(302312.6, 289731.2, 271116.8)
α = 1.0	(298343.8, 285550.0, 266554.8)

After this the decision maker establishes an aspiration level $\tilde{G}$ whose membership function is as follows (using equation 3.20).

$$\mu_{\tilde{G}}(z) = \begin{cases} 1 & if \quad z \geq 323166.3 \\ \dfrac{z - 266554.8}{323166.3 - 266554.8} & if \quad 323466.3 \leq z \leq 26655.4 \\ 0 & if \quad z \leq 266554.8 \end{cases}$$

It is fixed such that the DM is fully satisfied if objective value is higher than 323166.3 (maximum value from Table 3.11) and fully dissatisfied if objective value is lower than 266554.8 (minimum value from Table 3.11).

Now the compatibility index of each solution with DM aspiration is calculated using equation (3.21) and the values are:

$K_{\tilde{G}}(z(0.4)) = 0.78$ $\quad$ $K_{\tilde{G}}(z(0.5)) = 0.70$

$K_{\tilde{G}}(z(0.6)) = 0.62$ $\quad$ $K_{\tilde{G}}(z(0.7)) = 0.54$

$K_{\tilde{G}}(z(0.8)) = 0.46$ $\quad$ $K_{\tilde{G}}(z(0.9)) = 0.38$

$K_{\tilde{G}}(z(1)) = 0.31$

In order to find the balance solution between the feasibility degree and the degree of satisfaction, the membership degree of each α -acceptable optimal solution is calculated using equation (3.22) and the values are:

$$\mu_{\tilde{D}}(x(0.4)) = 0.4 \times 0.78 = 0.311$$

$$\mu_{\tilde{D}}(x(0.5)) = 0.5 \times 0.0.70 = 0.351$$

$$\mu_{\tilde{D}}(x(0.6)) = 0.6 \times 0.62 = 0.373$$

$$\mu_{\tilde{D}}(x(0.7)) = 0.7 \times 0.54 = 0.381$$

$$\mu_{\tilde{D}}(x(0.8)) = 0.8 \times 0.46 = 0.370$$

$$\mu_{\tilde{D}}(x(0.9)) = 0.9 \times 0.38 = 0.346$$

$$\mu_{\tilde{D}}(x(1)) = 1 \times 0.31 = 0.310$$

Therefore, the optimum feasibility degree is 0.7, which corresponds to the highest membership degree of 0.381. If the DM is not satisfied with this solution than the goal and its tolerance threshold can be changed to refine the result or refine the values of degree of feasibility. With a feasibility degree (α) = 0.7, the results show that to meet the customer demand, 1346 units of product 1 and 1256 units of product 2 are to be manufactured, with the possibilistic profit of USD (310834.5, 298775.0, 281012.9).

Table 3.12 shows the number of products to be collected and reused at the various collection/repair centers. The number of products disassembled at the disassembly centers are also shown in this table.

Table 3.12: Number of products collected (C_{jm}), reused (A_{jm}) and disassembled (R_{jn}) for α =0.7

	C_{jm}			A_{jm}			R_{jn}	
	m = 1	m = 2	m = 3	m = 1	m = 2	m = 3	n = 1	n = 2
j = 1	300	400	157	54	72	28	203	500
j = 2	200	300	300	36	54	54	256	400

Table 3.13: Number of parts purchased from external supplier (S_{ik}), number of parts disassembled (T_{in}), number of parts refurbished (F_{il}), number of parts recycled (Y_{in}) and number of parts disposed (W_{in}) for α =0.7

	S_{ik}			T_{in}		F_{il}		W_{in}		Y_{in}	
	k = 1	k = 2	k = 3	n = 1	n = 2	l = 1	l = 2	n = 1	n = 2	n = 1	n = 2
i = 1	4000	132	0	1174	2200	1500	828	200	374	164	308
i = 2	0	0	4993	1377	2700	1013	1800	235	459	192	378
i = 3	0	3329	0	918	1800	875	1000	157	306	128	252

Table 3.13 shows parts related decision variables, i.e. number of parts to be purchased from different external supplier and number of parts to be refurbished at each refurbishing center. All units of part 1are purchased from supplier 1 and 2, and nothing from supplier 3. Similarly, part 2 is purchased from supplier 3 only, while part 3 is purchased from supplier 2 only. Table 3.13 also shows the number of parts disassembled

(T_{in}), number of parts recycled (Y_{in}), and number of parts disposed off (W_{in}) from the various disassembly centers.

3.6. The Proposed Multi-Period CLSC Framework and Mathematical Model

This section extends the single period CLSC model to multi-time period CLSC model with inventory of products, parts and the related inventory costs. The multi-time period models with inventory of products and parts will assist to handle the uncertainty in demand and return of the returned products.

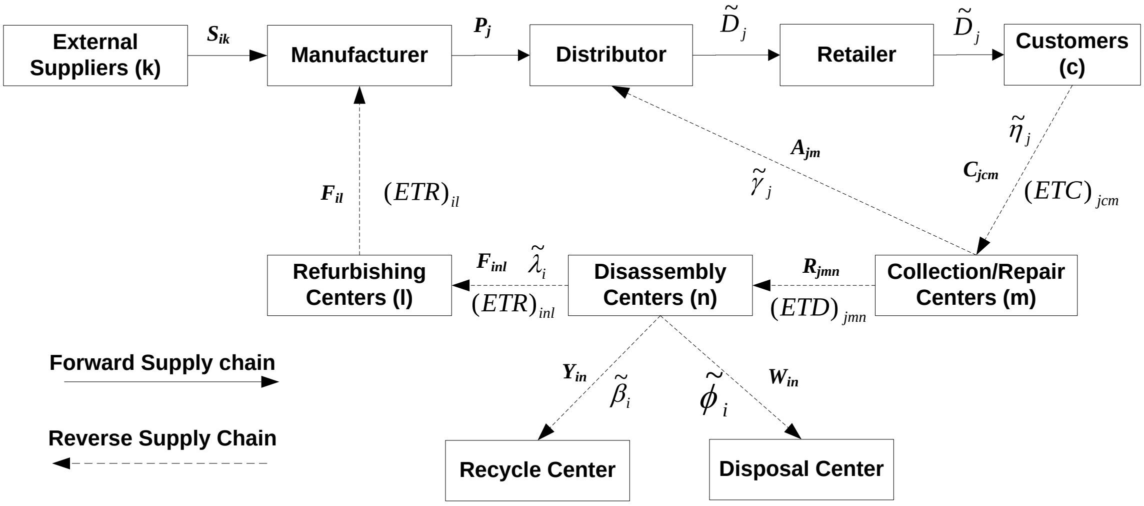

Figure 3.4: The proposed multi-period closed-loop supply chain framework

3.6.1 Description of the Proposed Multi-Period CLSC Framework

Figure 3.4 represents the proposed multi-period CLSC framework. The proposed multi-period CLSC model considers the inventory level of products and parts and the related inventory costs. Product recovery system again starts with the collection of retuned products, but now the collection centers also serves for the inventory of products in addition to collection and repair activities. Secondly after refurbishing process, the ‘as new’ parts are stocked as part inventory together with new parts purchased from the external supplier(s). Finally, parts from part inventory are supplied to the manufacturing plant according to the production plan. Moreover, most of parameters and decision variables are now function of time period.

3.6.2 The proposed fuzzy mixed-integer linear programming model

The proposed multi-period CLSC framework is further represented by fuzzy mixed integer linear programming (Fuzzy MILP) model for optimization. The indices, parameters and decision variables other than what defined in single period model (section 3.3.2) are given below:

Indices

t	set of time periods, $t = 1, 2, \ldots T$

Decision variables

P_{jt}	units of product *j* to be produced at time *t*
C_{jmt}	units of product *j* to be collected at collection center *m* at time *t*
A_{jmt}	units of product *j* to be reused from collection center *m* at time *t*
R_{jmnt}	units of product *j* to be disassembled at site *n* from collection center *m* at time *t*
$(PI)_{jmt}$	inventory level of product *j* at collection center *m* at time *t*
$(PrI)_{it}$	inventory level of part *i* at time *t*
S_{ikt}	units of part *i* to be purchased from supplier *k* at time *t*
T_{int}	units of part *i* to be disassembled at disassembly site *n* at time *t*
F_{inlt}	units of parts *i* to be refurbished at site *l* from disassembly center *n* at time *t*
F_{ilt}	units of part *i* to be refurbished at refurbishing center *l* at time *t*
W_{int}	units of part *i* to be disposed off from disassembly center *n* at time *t*
Y_{int}	units of part *i* to be recycled from disassembly center *n* at time *t*
B_{jmt}	binary variable for set-up of collection facility for product *j* at *m* at time *t*
V_{jnt}	binary variable for set-up of disassembly site for product *j* at *n* at time *t*
U_{ilt}	binary variable for set-up of refurbishing site for part *i* at *l* at time *t*

Parameters

$\tilde{D}_{jt}$	Demand of product *j* to be produced at time *t*
$(MP)_{jt}$	Capacity of product *j* to be produced by the plant at time *t*

$(MC)_{jmt}$	Capacity of the collection center *m* for product *j* at time *t*
$(MD)_{jnt}$	Capacity of the disassembly center *n* for product *j* at time *t*
$(MR)_{ilt}$	Capacity of the refurbishing center *l* for part *i* at time *t*
$(\mathrm{Pr}\widetilde{I}C)_{it}$	The unit inventory cost of part *i* at time *t*
$(P\widetilde{I}C)_{jmt}$	The unit inventory cost of product *j* at collection center *m* at time *t*

As defined previously that symbols with a tilde (~) at the top indicated the parameters with uncertainty and are estimated by appropriate possibility distribution.

Objective Function

Maximize

$$\begin{aligned}
&\sum_t\sum_j(\widetilde{PF}_j)*(P_{jt}+\sum_m A_{jmt})+\sum_t\sum_n\sum_i(\widetilde{RP})_i*Y_{\mathrm{int}}-\sum_t\sum_k\sum_i(\widetilde{PC})_{ik}*S_{ikt}\\
&-\sum_t\sum_m\sum_j(\widetilde{CC})_{jm}*C_{jmt}-\sum_t\sum_m\sum_j(\widetilde{SC})_{jm}*B_{jmt}-\sum_t\sum_m\sum_j(\widetilde{UC})_{jm}*A_{jmt}\\
&-\sum_t\sum_n\sum_i(\widetilde{DC})_{in}*T_{\mathrm{int}}-\sum_t\sum_n\sum_j(\widetilde{SD})_{jn}*V_{jnt}-\sum_t\sum_l\sum_i(\widetilde{RC})_{il}*F_{ilt}\\
&-\sum_t\sum_l\sum_i(\widetilde{SR})_{il}*U_{il}-\sum_t\sum_n\sum_i(\widetilde{WDC})_i*W_{\mathrm{int}}-\sum_t\sum_j\sum_m(\widetilde{RF})_{jm}*C_{jmt}\\
&-\sum_t\sum_j\sum_m\sum_n(\widetilde{TCD})_{jmn}*R_{jmnt}-\sum_t\sum_i\sum_n\sum_l(\widetilde{TCR})_{inl}*F_{inlt}-\sum_t\sum_j\sum_m(\widetilde{TCU})_{jm}*A_{jmt}\\
&-\sum_t\sum_i(\mathrm{Pr}\widetilde{I}C)_{it}*(\mathrm{Pr}I)_{it}-\sum_t\sum_j\sum_m(P\widetilde{I}C)_{jmt}*(PI)_{jmt}
\end{aligned} \tag{3.23}$$

Subject to

$$\widetilde{D}_{jt}=P_{jt}+\sum_m A_{jmt}\qquad \forall j,t \tag{3.24}$$

$$C_{jmt}+(PI)_{jm,t-1}=A_{jmt}+\sum_n R_{jmnt}+(PI)_{jmt}\qquad \forall j,m,t \tag{3.25}$$

$$T_{\mathrm{int}}=Y_{\mathrm{int}}+W_{\mathrm{int}}+\sum_l F_{inlt}\qquad \forall i,n,t \tag{3.26}$$

$$\sum_j q_{ij}*P_{jt}+(\mathrm{Pr}I)_{it}=\sum_l F_{ilt}+\sum_k S_{ikt}+(\mathrm{Pr}I)_{i,t-1}\qquad \forall i,t \tag{3.27}$$

$$T_{\mathrm{int}}=\sum_m\sum_j q_{ij}R_{jmnt}\qquad \forall i,n,t \tag{3.28}$$

$$F_{ilt}=\sum_n F_{inlt}\qquad \forall i,l,t \tag{3.29}$$

$$R_{jnt}=\sum_m R_{jmnt}\qquad \forall j,n,t \tag{3.30}$$

$$\sum_{m} C_{jmt} \le \tilde{\eta}_j * \tilde{D}_{jt} \qquad \forall j,t \tag{3.31}$$

$$A_{jmt} \le \tilde{\gamma}_j * C_{jmt} \qquad \forall j,m,t \tag{3.32}$$

$$\sum_{l} F_{inlt} \le \tilde{\lambda}_i * T_{\text{int}} \qquad \forall i,n,t \tag{2.33}$$

$$Y_{\text{int}} \le \tilde{\beta}_i * T_{\text{int}} \qquad \forall i,n,t \tag{3.34}$$

$$C_{jmt} \le (MC)_{jmt} * B_{jmt} \qquad \forall j,m,t \tag{3.35}$$

$$\sum_{m} R_{jmnt} \le (MD)_{jnt} * V_{jnt} \qquad \forall j,n,t \tag{3.36}$$

$$\sum_{n} F_{inl} \le (MR)_{ilt} * U_{il} \qquad \forall i,l \tag{3.37}$$

$$(MNS)_k \le \sum_{i} S_{ikt} \le (MXS)_k \qquad \forall k,t \tag{3.38}$$

$$P_{jt} \le (MP)_{jt} \qquad \forall j,t \tag{3.39}$$

$$B_{jmt}, V_{jnt}, U_{ilt} \quad \in \{0,1\} \qquad \forall i,j,m,n,l,t \tag{3.40}$$

$$P_{jt}, C_{jmt}, A_{jmt}, R_{jmnt}, R_{jnt}, S_{ikt}, T_{\text{int}}, F_{inlt}, F_{ilt}, W_{\text{int}}, Y_{\text{int}}, PI_{jmt}, \Pr I_{it} \quad \in I \qquad \forall j,m,n,l,i,k,t \tag{3.41}$$

Equation (3.23) represents the objective function of the multi-period CLSC model i.e. to maximize the profit to the organization. Constraint (3.24) ensures that demand for each product is satisfied with the sum of newly produced products and reused products. Equation (3.25), (3.26) and (3.27) represents the flow balance constraint at collection center, disassembly center and refurbishing center respectively. While equation (3.28), (3.29) and (3.30) calculate the number of parts at disassembly centers, number of parts at refurbishing centers and number of products at disassembly centers respectively. Constraints (3.31), (3.32), (3.33), and (3.34) provide the maximum limit on the number of products collected, number of products reused, number of parts refurbished and number of parts to be recycled respectively. Constraints (3.35), (3.36), (3.37) and (3.38) ensure the capacity limit for collection center, disassembly center, refurbishing center, and plant respectively. Constraint (3.39) ensures the maximum and minimum capacity of the external suppliers. Constraints (3.40) and (3.41) are related to binary and general integer values of the decision variables. All the decision variables are positive numbers.

3.7. The Proposed Solution Methodology

The various steps to solve the proposed multi-period CLSC model are same as provided in section 3.4.

Crisp MILP of multi-period Fuzzy MILP model

The equivalent crisp model of multi-period Fuzzy MILP model is presented below:

Maximize

$$\begin{aligned}
&\sum_t\sum_j\left(\frac{PF_j^{pes}+2\times PF_j^{mos}+PF_j^{opt}}{4}\right)*(P_{jt}+\sum_m A_{jmt})+\sum_t\sum_n\sum_i\left(\frac{RP_i^{pes}+2\times RP_i^{mos}+RP_i^{opt}}{4}\right)*Y_{\text{int}}\\
&-\sum_t\sum_k\sum_i\left(\frac{PC_{ik}^{pes}+2\times PC_{ik}^{mos}+PC_{ik}^{opt}}{4}\right)*S_{ikt}-\sum_t\sum_m\sum_j\left(\frac{CC_{jm}^{pes}+2\times CC_{jm}^{mos}+CC_{jm}^{opt}}{4}\right)*C_{jmt}\\
&-\sum_t\sum_m\sum_j\left(\frac{SC_{jm}^{pes}+2\times SC_{jm}^{mos}+SC_{jm}^{opt}}{4}\right)*B_{jmt}-\sum_t\sum_m\sum_j\left(\frac{UC_{jm}^{pes}+2\times UC_{jm}^{mos}+UC_{jm}^{opt}}{4}\right)*A_{jmt}\\
&-\sum_t\sum_n\sum_i\left(\frac{DC_{in}^{pes}+2\times DC_{in}^{mos}+DC_{in}^{opt}}{4}\right)*T_{\text{int}}-\sum_t\sum_n\sum_j\left(\frac{SD_{jn}^{pes}+2\times SD_{jn}^{mos}+SD_{jn}^{opt}}{4}\right)*V_{jnt}\\
&-\sum_t\sum_l\sum_i\left(\frac{RC_{il}^{pes}+2\times RC_{il}^{mos}+RC_{il}^{opt}}{4}\right)*F_{ilt}-\sum_t\sum_l\sum_i\left(\frac{SR_{il}^{pes}+2\times SR_{il}^{mos}+SR_{il}^{opt}}{4}\right)*U_{ilt}\\
&-\sum_t\sum_n\sum_i\left(\frac{WDC_i^{pes}+2\times WDC_i^{mos}+WDC_i^{opt}}{4}\right)*W_{in}-\sum_t\sum_j\sum_m\left(\frac{RF_{jm}^{pes}+2\times RF_{jm}^{mos}+RF_{jm}^{opt}}{4}\right)*C_{jmt}\\
&-\sum_t\sum_j\sum_m\sum_n\left(\frac{TCD_{jmn}^{pes}+2\times TCD_{jmn}^{mos}+TCD_{jmn}^{opt}}{4}\right)*R_{jmnt}-\sum_t\sum_i\sum_n\sum_l\left(\frac{TCR_{inl}^{pes}+2\times TCR_{inl}^{mos}+TCR_{inl}^{opt}}{4}\right)*F_{inlt}\\
&-\sum_t\sum_j\sum_m\left(\frac{TCU_{jm}^{pes}+2\times TCU_{jm}^{mos}+TCU_{jm}^{opt}}{4}\right)*A_{jmt}-\sum_t\sum_i\left(\frac{\Pr IC_{it}^{pes}+2\times \Pr IC_{it}^{mos}+\Pr IC_{it}^{opt}}{4}\right)*(\Pr I)_{it}\\
&-\sum_t\sum_j\sum_m\left(\frac{PIC_{jmt}^{pes}+2\times PIC_{jmt}^{mos}+PIC_{jmt}^{opt}}{4}\right)*(PI)_{jmt}
\end{aligned}$$

The crisp equivalents of constraints given by equation number 3.20, 3.27, 3.28, 3.29 and 3.30 are as follows. The other constraints remain as such.

$$\left(\frac{D_{jt}^{pes}+2\times D_{jt}^{mos}+D_{jt}^{opt}}{4}\right)=P_{jt}+\sum_m A_{jmt}\quad \forall j,t$$

$$\sum_{m} C_{jmt} \le \left[\alpha\left(\frac{\eta_j^{pes}+\eta_j^{mos}}{2}\right)+(1-\alpha)\left(\frac{\eta_j^{opt}+\eta_j^{mos}}{2}\right)\right]*\left[\alpha\left(\frac{D_{jt}^{pes}+D_{jt}^{mos}}{2}\right)+(1-\alpha)\left(\frac{D_{jt}^{opt}+D_{jt}^{mos}}{2}\right)\right] \qquad \forall j,t$$

$$A_{jmt} \le \left[\alpha\left(\frac{\gamma_j^{pes}+\gamma_j^{mos}}{2}\right)+(1-\alpha)\left(\frac{\gamma_j^{opt}+\gamma_j^{mos}}{2}\right)\right]*C_{jmt} \qquad \forall j,m,t$$

$$\sum_{l} F_{inlt} \le \left[\alpha\left(\frac{\lambda_i^{pes}+\lambda_i^{mos}}{2}\right)+(1-\alpha)\left(\frac{\lambda_i^{opt}+\lambda_i^{mos}}{2}\right)\right]*T_{\text{int}} \qquad \forall i,n,t$$

$$Y_{\text{int}} \le \left[\alpha\left(\frac{\beta_i^{pes}+\beta_i^{mos}}{2}\right)+(1-\alpha)\left(\frac{\beta_i^{opt}+\beta_i^{mos}}{2}\right)\right]*T_{\text{int}} \qquad \forall i,n,t$$

3.8. An Illustrative Example for Multi-Period CLSC Model

This section presents a numerical example to illustrate how the proposed model works in a multi-time, multi-product, multi-echelon CLSC framework under an uncertain environment. The problem presented in single time period model (section 3.5) is extended to include the data on multi-period demand, multi-period capacity of collection, disassembly and refurbishing centers, and the multi-period inventory cost of product and parts. It is assumed that there are two types of products and each product is made of three types of parts with different utilization factor. The demand and production capacity for each product is provided in Table 3.14. In the network it is considered that there are three collection/repair centers, two disassembly centers, two refurbishing centers, three external suppliers, one recycle center, and one disposal center. Inventory of products is maintained at the collection centers and part inventory is done at part inventory center. Both the initial inventory and minimum inventory of products and parts is 10 and 25 respectively. The capacity of collection center, disassembly center, and refurbishing center for different periods is provided in Tables 3.15, 3.16 and 3.17 respectively. The inventory cost for each product and part is shown in Table 3.18 and 3.19 respectively. The maximum purchase order for each supplier is 8000, 9000 and 9000, and the minimum purchase order for each supplier is 100. The rest of input parameters can be had from section 3.6.

Table 3.14: The demand of each product and production capacity in different time periods

	Demand (D_{jt})			**Production Capacity (MP_{jt})**		
	Period 1	Period 2	Period 3	Period 1	Period 2	Period 3
$j = 1$	(1400,1500,1600)	(1200,1300,1400)	(1500,1600,1700)	1700	1600	1800
$j = 2$	(1300,1400,1500)	(1100,1200,1300)	(1400,1500,1600)	1500	1400	1600

Table 3.15: The collection capacity for each product in different time periods

$(MC)_{jmt}$	**Period 1**			**Period 2**			**Period 3**		
	$m = 1$	$m = 2$	$m = 3$	$m = 1$	$m = 2$	$m = 3$	$m = 1$	$m = 2$	$m = 3$
$j = 1$	300	400	300	250	350	250	400	500	400
$j = 2$	350	300	300	300	250	250	450	400	400

Table 3.16: The disassembly capacity for each product in different time periods

$(MD)_{jnt}$	**Period 1**		**Period 2**		**Period 3**	
	$n = 1$	$n = 2$	$n = 1$	$n = 2$	$n = 1$	$n = 2$
$j = 1$	500	500	450	450	600	600
$j = 2$	500	400	450	400	600	500

Table 3.17: The refurbishing capacity for each part at different time periods

$(MR)_{ilt}$	**Period 1**		**Period 2**		**Period 3**	
	$l = 1$	$l = 2$	$l = 1$	$l = 2$	$l = 1$	$l = 2$
$i = 1$	2500	2800	2450	2650	2500	2800
$i = 2$	2000	2800	2550	2750	2000	2800
$i = 3$	2500	2000	2450	2950	2500	2000

Table 3.18: The inventory cost for each product in different time periods

$(P\tilde{I}C)_{jmt}$	**Period 1**			**Period 2**			**Period 3**		
	$m = 1$	$m = 2$	$m = 3$	$m = 1$	$m = 2$	$m = 3$	$m = 1$	$m = 2$	$m = 3$
$j = 1$	(6,7,8)	(7,8,9)	(8,9,10)	(7,8,9)	(8,9,10)	(9,10,11)	(6,7,8)	(7,8,9)	(8,9,10)
$j = 2$	(7,8,9)	(8,9,10)	(8,9,10)	(8,9,10)	(9,10,11)	(9,10,11)	(7,8,9)	(8,9,10)	(8,9,10)

Table 3.19: The inventory cost for each part in different time periods

$(\Pr\tilde{I}C)_{it}$	Period 1	Period 2	Period 3
i= 1	(2,3,4)	(3,4,5)	(2,3,4)
i = 2	(3,4,5)	(4,5,6)	(3,4,5)
i = 3	(4,5,6)	(5,6,7)	(4,5,6)

The proposed model is solved using IBM ILOG Optimization Studio 12.2 on intel core i5 processor machine. The model contains 476 constrains, 303 variables, 252 integers, and 1667 non-zeros. As the optimum value of objective function depends on the degree of feasibility of constraints, i.e. higher the degrees of feasibility lower the value of objective function. So to find the optimum value of degree of feasibility, all the α-acceptable optimal solutions are calculated (with the minimum α = 0.4) as shown in Table 3.20. From Table 3.20 it can be observed that with the increase in degree of feasibility the value of objective function is getting reduced.

Table 3.20: α-acceptable optimal solutions

Feasibility degree, α	Possibility distribution of the objective value, $\tilde{z}(\alpha)$	$K_{\tilde{G}}(z(\alpha))$	$\mu_{\tilde{D}}(x(\alpha))$
α = 0.4	877060, 934931, 992790	0.84	0.334
α = 0.5	851470, 910855, 970230	0.77	0.383
α = 0.6	815180, 873699, 932210	0.66	0.393
α = 0.7	775800, 832222, 888630	0.53	0.373
α = 0.8	735590, 788663, 841720	0.40	0.322
α = 0.9	694710, 743159, 791600	0.27	0.241
α = 1	654960, 697597, 740160	0.13	0.131

This establishes an aspiration level $\tilde{G}$ (with maximum value = 992790 and minimum value = 654960) whose membership function is as follows (using equation 3.20).

$$\mu_{\tilde{G}}(z) = \begin{cases} 1 & if \quad z \geq 992790 \\ \dfrac{z-654960}{992790-654960} & if \quad 992790 \leq z \leq 654960 \\ 0 & if \quad z \leq 654960 \end{cases}$$

In order to find the balanced solution between the feasibility degree and the degree of satisfaction, compatibility index and membership degree of each α–acceptable optimal solution is calculated using equations (3.21) and (3.22) respectively. Membership degree of each α–acceptable optimal solution is shown in last column of Table 3.20. The optimum feasibility degree is 0.6, which corresponds to the highest membership degree of 0.393. If the decision maker is not satisfied with this solution than the goal and its tolerance threshold can be changed to refine the result or refine the values of degree of feasibility.

3.9. Results and Discussion

With a feasibility degree (α) of 0.6, Table 3.21 provides the number of products to be manufacturer to meet the customer demand, with a probabilistic profit of USD (815180, 873699, 932210). Table 3.22 and Table 3.23 shows the number of products to be collected and reused at the various collection/repair centers respectively. Table 3.24 shows the number of products disassembled at disassembly centers, while Table 3.25 and Table 3.26 shows the number of parts disposed and recycled from each disassembly center respectively. The number of parts refurbished at each refurbishing center are shown in Table 3.27 and Table 3.28 shows the number of parts purchased from each external supplier to fulfill the production demand. Table 3.28 shows that part1, part2 and part3 are purchased from supplier1, supplier 3 and supplier2 respectively. The product inventory and part inventory are shown in Table 3.29 and Table 3.30 respectively. The optimum flow of products and parts at time period-1 is shown in Figure 3.5. The number on arrows represents the number of products (product1, product2) or parts (part1, part2, part3) moving from one facility center to another.

The managerial implication of the proposed CLSC framework and optimization model is that it considers the different costs (like incentive to customer, processing and set-up cost at facility centers, transportation cost, profit from recycling and waste disposal cost), different product recovery options (like reuse, recycle, refurbishing and disposal), and uncertainty in parameters (like demand of product, unit cost of collection, disassembly, refurbishing and disposal, set-up cost at each facility center, capacity of each facility center, unit purchasing cost and maximum percentage of parts that can be reused, refurbished recycled and disposed) simultaneously in the model. The developed model will help the organizations to calculate the optimal number of products to be remanufactured and the optimal number of parts to be purchased from external suppliers to maximize the profit of organization. It also provides the optimal location and allocation to different collection centers, disassembly centers, refurbishing centers and external suppliers.

Table 3.21: The number of products to be manufactured in different time periods

P_{jt}	**Period 1**	**Period 2**	**Period 3**
$j = 1$	1365	1183	1456
$j = 2$	1274	1092	1365

Table 3.22: The number of products collected at each collection center in different time periods

C_{jmt}	**Period 1**			**Period 2**			**Period 3**		
	$m = 1$	$m = 2$	$m = 3$	$m = 1$	$m = 2$	$m = 3$	$m = 1$	$m = 2$	$m = 3$
$j = 1$	300	400	146	250	350	135	400	500	2
$j = 2$	190	300	300	179	250	250	46	400	400

Table 3.23: The number of products reused from each collection centers in different time periods

A_{jmt}	**Period 1**			**Period 2**			**Period 3**		
	$m = 1$	$m = 2$	$m = 3$	$m = 1$	$m = 2$	$m = 3$	$m = 1$	$m = 2$	$m = 3$
$j = 1$	48	64	23	40	56	21	64	80	0
$j = 2$	30	48	48	28	40	40	7	64	64

Table 3.24: The number of products disassembled at each disassembly center in different time periods

R_{jnt}	Period 1		Period 2		Period 3	
	$n = 1$	$n = 2$	$n = 1$	$n = 2$	$n = 1$	$n = 2$
$j = 1$	211	500	168	450	158	600
$j = 2$	264	400	171	400	211	500

Table 3.25: The number of parts disposed from each disassembly center in different time periods

W_{int}	Period 1		Period 2		Period 3	
	$n = 1$	$n = 2$	$n = 1$	$n = 2$	$n = 1$	$n = 2$
$i = 1$	213	385	149	368	167	473
$i = 2$	250	473	179	447	195	578
$i = 3$	167	315	119	298	130	385

Table 3.26: The number of parts recycled from each disassembly center in different time periods

Y_{int}	Period 1		Period 2		Period 3	
	$n = 1$	$n = 2$	$n = 1$	$n = 2$	$n = 1$	$n = 2$
$i = 1$	176	319	123	304	137	391
$i = 2$	206	391	147	369	160	478
$i = 3$	137	261	98	246	107	319

Table 3.27: The number of parts at each refurbishing center in different time periods

F_{ilt}	Period 1		Period 2		Period 3	
	$l = 1$	$l = 2$	$l = 1$	$l = 2$	$l = 1$	$l = 2$
$i = 1$	2321	0	2005	0	2481	0
$i = 2$	5	2800	0	2425	196	2800
$i = 3$	0	1870	0	1617	0	1997

Table 3.28: The number of parts purchased from each external suppliers in different time periods

S_{ikt}	Period 1			Period 2			Period 3		
	$k = 1$	$k = 2$	$k = 3$	$k = 1$	$k = 2$	$k = 3$	$k = 1$	$k = 2$	$k = 3$
$i = 1$	4231	0	0	3637	0	0	4526	0	0
$i = 2$	0	0	5112	0	0	4400	0	0	5467
$i = 3$	0	3408	0	0	2933	0	0	3645	0

Table 3.29: Product inventory at each collection center in different time periods

PI_{jmt}	Period 1			Period 2			Period 3		
	$m = 1$	$m = 2$	$m = 3$	$m = 1$	$m = 2$	$m = 3$	$m = 1$	$m = 2$	$m = 3$
$j = 1$	10	10	10	10	10	10	10	10	10
$j = 2$	10	10	10	10	10	10	10	10	10

Table 3.30: Part inventory in different time periods

	Period 1	Period 2	Period 3
$i = 1$	25	25	25
$i = 2$	25	25	25
$i = 3$	25	25	25

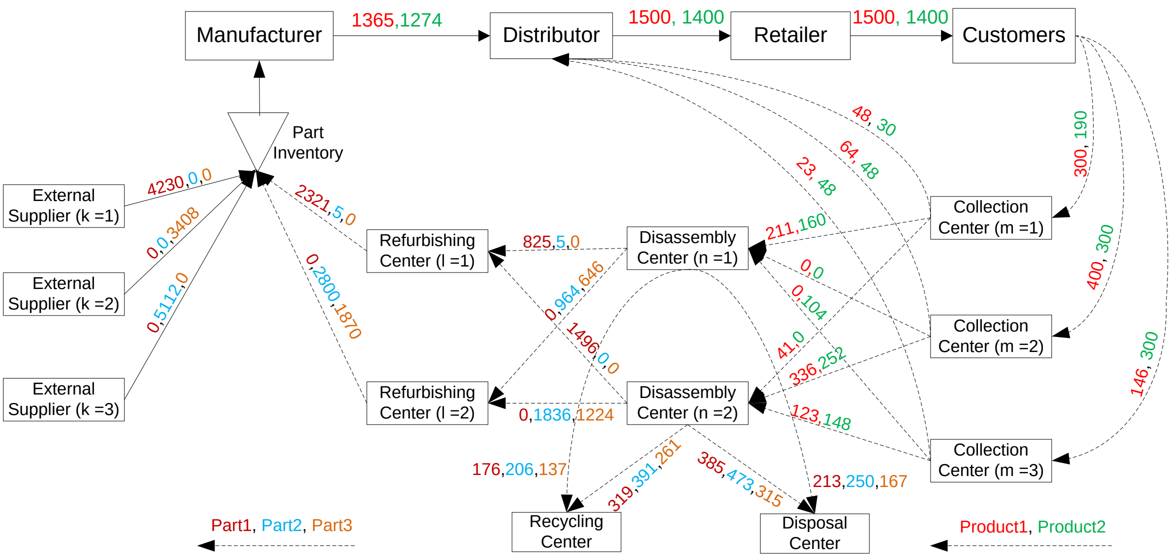

Figure 3.5: Optimum flow of products and parts at first period

3.10. Summary

In this chapter a multi-product, multi-echelon capacitated closed-loop supply chain framework is proposed for single time period, which is further extended to multi-period with inventory flow in an uncertain environment. The models consider multiple collection centers, multiple disassembly centers, multiple refurbishing centers, and multiple external suppliers to take care of purchasing cost, transportation cost, inventory cost, processing cost, set-up cost, and capacity constraints simultaneously. The uncertainties related to ill-known parameters are represented by triangular fuzzy numbers. Fuzzy mixed-integer linear programming models are proposed to represent the proposed frameworks in mathematical terms for optimization. The proposed solution methodology is able to generate a balanced solution between the feasibility degree and the degree of satisfaction.

The effectiveness of the developed fuzzy optimization model as well as the usefulness of the proposed solution approach is investigated by solving illustrative examples. The proposed closed-loop supply chain framework and mathematical model can be customized for various industries. An illustrative example has been solved by using LINGO 13 for single period model and for multi-period model it is solved by IBM ILOG CPLEX Optimization Studio 12.2. The proposed CLSC models are based on the single objective optimization i.e. considering the economic aspects only; which will further be extended to multi-objective model considering the economical and environmental factors of sustainability in closed-loop supply chain.

CHAPTER 4

MULTI-OBJECTIVE CLOSED-LOOP SUPPLY CHAIN DESIGN AND OPTIMIZATION

The growing concern for sustainability has forced the researchers and managers to incorporate the environmental and social factors along with the economical factors in the design of supply chains. This chapter presents the design and optimization of a multi-objective closed-loop supply chain considering the economical and environmental factors with uncertainty in parameters. The proposed network is modeled as fuzzy multi-objective mixed integer linear programming problem considering multi-customer zones, multi-collection centers, multi-disassembly centers, multi-refurbishing centers, multi-external suppliers, and different product recovery processes; to take care of purchasing cost, transportation cost, processing cost, set-up cost, and capacity constraints simultaneously. The model is solved using an interactive ε-constraint method. A case example is solved using LINGO 14.0 to demonstrate the significance and applicability of the developed fuzzy optimization model as well as the usefulness of the proposed solution approach.

4.1. Introduction

Due to the increasing concern for environmental and corporate social responsibility, the design of closed-loop supply chain with only economical parameters is insufficient to achieve sustainability. The increasing importance of this field; academically, socially, and economically; is reflected by the geometric growth of related scientific publications during the past two decades and especially so in the past decade (Min and Kim 2012). Therefore, this chapter extends the single objective CLSC model developed in the previous chapter to multi-objective CLSC model considering economical as well as environmental objectives. It is one of the most important strategic decisions in supply chain management and plays an important role in overall economic and environmental performance of the supply chains. Therefore, the network design and optimization of a multi-objective CLSC is more difficult when compared with traditional or forward supply chain. However, the mathematical modeling of environmental factors has been a challenge for the researchers. The environmental factors are modeled using life cycle assessment tools. In this model refund or incentive to customer is considered as the social factor of sustainability and is integrated with economical objective function. As discussed before another challenge to the design and manufacturing of CLSC is the integration of parts remanufactured with the parts purchased from external supplier to meet the customer demand. Moreover, because of the uncertainty in quantity, quality and time of return in CLSC, the product demand, cost parameters, and fraction of parts recovered for reuse, refurbish, recycle and disposal are also uncertain (Guide *et al.* 2000). So, assigning a crisp value to these parameters is difficult for the experts. Some of the relevant literature applies stochastic programming approaches for these types of problems (El-Sayed *et al.* 2010; Listeş and Dekker 2005). But the non availability of sufficient historical data in real-life cases and the high computational complexity makes the use of stochastic programming models non pragmatic. Therefore, fuzzy mathematics is used to handle the uncertainty of the ill-known parameters in the present model (as discussed in Section 3.2).

It has been observed in Section 2.4.2 and Table 2.7 that in last few years some papers have considered the optimization of economic and environmental factors in the design of CLSC (Amin and Zhang 2013; Krikke *et al.* 2003; Özceylan and Paksoy 2012; Pati *et al.* 2008; Pishvaee and Razmi 2012; Wang and Huang 2012). In most of these paper uncertainty in parameters is handled by senstivity analysis or scenerio analysis, but rarely with fuzzy numbers. Moreover, it has been identifed that there are many types of costs or product recovery options which have not been considered by the researcers in totality. This motivated to design a multi-objective CLSC model using fuzzy parameters that considers not only the economical but also the environmental factors of sustainability.

The first objective is to maximize the profit of the organization by optimally deciding the number of products to be remanufactured and number of parts to be purchased from external suppliers along with location and allocation of different facility centers, while the second objective is to minimize the environmental impact in the reverse supply chain. The environmental impact is measured in terms of carbon footprints using Eco-indicator 2.2 database. The objective function has been modeled as fuzzy mixed-integer linear programming problem and solved by using ε-constraint method. The advantage of ε-constraint method is that it provides all the efficient solutions (or a sufficient representation) by generating non-extreme efficient solutions and unsupported efficient solutions. It helps the decision maker to see the whole solution set and select the most preferred one. Moreover, the solution obtained with ε-constraint method is not affected by scaling of the objective function (Mavrotas 2009). Also, this model uses an efficient solution approach that is able to generate both balanced and unbalanced solutions by making a reasonable trade-off between environmental and economic objectives. The proposed model is solved using LINGO 14.0, an optimization tool. The proposed model:

(i) considers the economic and environmental factors in the design of the closed-loop supply chain network, the social factor is considered in terms of refund to customers and integrated in economical objective as suggested by Harraz and Galal (2011),

(ii) integrates the forward and reverse supply chain networks including different product recovery options,

(iii) integrates a LCA based quantitative environmental impact assessment method, i.e., eco-indicator 2.2, to access the environmental impact of reverse supply chain network,

(iv) handle the epistemic uncertainty in parameters due to unavailability or incompleteness of the data, and

(v) considers processing costs and set-up costs at collection centers, disassembly centers, refurbishing centers; transportation costs for each transportation link among facilities; disposal cost; direct purchase cost from external supplier; and profit from recycler.

4.2. The Proposed Multi-Objective CLSC Framework

A multi-product, multi-echelon, multi-objective CLSC framework is presented in Figure 4.1) which considers forward flow, reverse flow and their mutual interactions simultaneously. This framework is an extension of the single objective CLSC framework presented in the last chapter. The proposed framework considers minimization of environmental effects in terms of carbon footprint of transportation in reverse supply chain and maximization of profit to the organization as discussed in the last chapter. The proposed framework also have multiple customer zones. The network is structured as a typical five-echelon forward supply chain and five-echelon reverse supply chain. The flow of products, parts and assumptions are the same as described in section 3.3.1.

The two objectives of closed-loop supply chain are described here.

4.2.1 Economical objective

From the economical point of view the organization needs to maximize the total profit while meeting part demand from manufacturing plant. For this the organization needs to know how many products should be taken into the remanufacturing process and how many new parts to be purchased from the external supplier(s) in an uncertain environment. As there are multiple customer zones, collection centers, disassembly centers, and refurbishing centers so the model not only provides that how many products/parts to be processed, but also at which facility center(s). Similarly, it provides how many parts to be purchased from which external supplier. The model considers multi-product with different reuse, refurbish, disposal and recycling fractions.

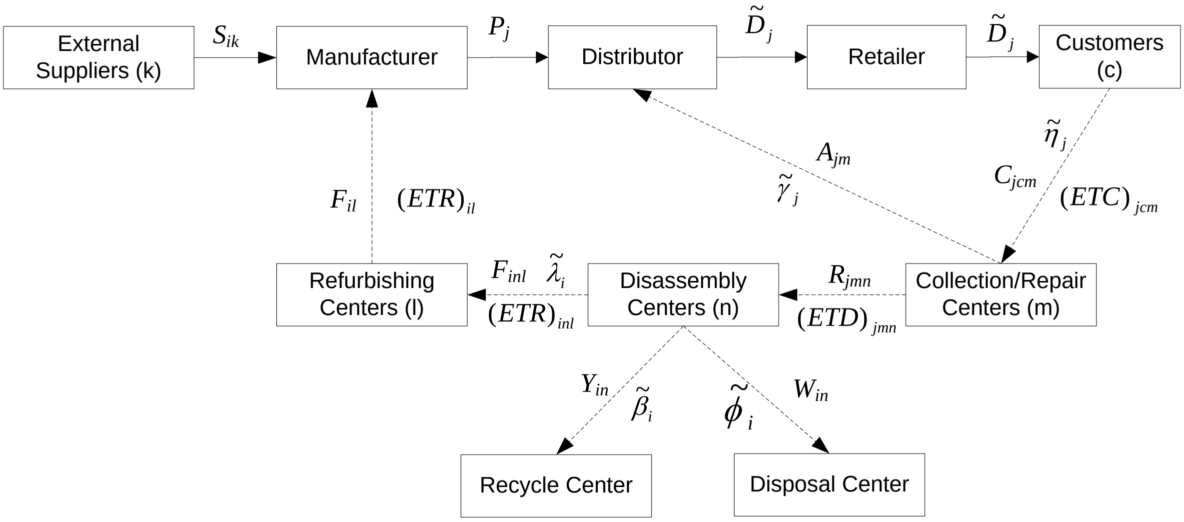

Figure 4.1: The proposed sustainable closed loop supply chain framework

4.2.2 Environmental objective

Some measures exist for the environmental evaluation of industrial activities like acidification potential, toxicity, climate change potential, etc. Climate change is an important and burning issue worldwide as it affects a large size of population. Climate change potential of an activity can be measured by its carbon footprints. Therefore, in this paper the environmental impact is measured in terms of carbon footprints of transportation in the reverse supply chain. Eco-invent 2.2 database (Ecoinvent Centre 2010) is used to calculate the carbon footprints with units of Kg of CO_2/tKm.

4.3. The Proposed Multi-Objective Fuzzy MILP Model

The indices, parameters and decision variables used to formulate the multi-objective fuzzy MILP model are described below.

Indices

i	set of parts, $i = 1, 2, \ldots..I$
j	set of products, $j = 1, 2, \ldots..J$
k	set of suppliers, $k = 1, 2, \ldots..K$
l	set of refurbishing centers, $l = 1, 2, \ldots..L$
m	set of collection/repair centers, $m = 1, 2, \ldots..M$
n	set of disassembly centers, $n = 1, 2, \ldots..N$
c	set of customer zones, c = 1,2,…C

Decision variables

P_j	number of product $j \in J$ to be produced
C_{jcm}	number of product $j \in J$ to be collected at collection center $m \in M$ from customer zone $c \in C$
C_{jm}	number of product $j \in J$ to be collected at collection center $m \in M$
A_{jm}	number of product $j \in J$ to be reused from collection center $m \in M$
R_{jmn}	number of product $j \in J$ to be disassembled at site $n \in N$ from collection center $m \in M$
S_{ik}	number of part $i \in I$ to be purchased from supplier $k \in K$
T_{in}	number of part $i \in I$ to be obtained at disassembly site $n \in N$
F_{inl}	number of parts $i \in I$ to be refurbished at site $l \in L$ from disassembly center $n \in N$
F_{il}	number of part $i \in I$ to be refurbished at refurbishing center $l \in L$
W_{in}	number of part $i \in I$ to be disposed from disassembly center $n \in N$
Y_{in}	number of part $i \in I$ to be recycled from disassembly center $n \in N$
B_{jm}	binary variable for set-up of collection facility for product $j \in J$ at $m \in M$
V_{jn}	binary variable for set-up of disassembly site for product $j \in J$ at $n \in N$
U_{il}	binary variable for set-up of refurbishing site for part $i \in I$ at $l \in L$

Parameters

$\tilde{D}_j$	demand for product $j \in J$
q_{ij}	number of units of parts $i \in I$ in product $j \in J$
$P\tilde{F}_j$	profit on selling product $j \in J$
$(MP)_j$	maximum capacity of the plant for product $j \in J$
$(C\tilde{C})_{jm}$	unit cost of collection and inspection for product $j \in J$ at collection center $m \in M$
$(S\tilde{C})_{jm}$	set-up cost for collection of product $j \in J$ at center $m \in M$
$(MC)_{jm}$	maximum capacity of collection center $m \in M$ for product $j \in J$
$(D\tilde{C})_{in}$	unit cost of disassembly for part $i \in I$ at disassembly center $n \in N$
$(S\tilde{D})_{jn}$	unit set-up cost for disassembly of product $j \in J$ at center $n \in N$
$(MD)_{jn}$	maximum capacity of disassembly center $n \in N$ for product $j \in J$
$(R\tilde{C})_{il}$	unit cost of refurbishing for part $i \in I$ at center $l \in L$
$(S\tilde{R})_{il}$	unit set-up cost for refurbishing of part $i \in I$ at center $l \in L$
$(MR)_{il}$	maximum capacity of refurbishing center $l \in L$ for part $i \in I$
$(U\tilde{C})_{jm}$	unit cost of repair for product $j \in J$ from collection center $m \in M$
$(W\tilde{D}C)_i$	unit cost of disposal for part $i \in I$
$(R\tilde{P})_i$	unit profit from recycling for part $i \in I$
$(RF)_{jm}$	unit cost of refund to customers for product $j \in J$
$(P\tilde{C})_{ik}$	unit purchasing cost for part $i \in I$ from supplier $k \in K$
$(MXS)_k$	maximum purchase order from supplier $k \in K$
$(MNS)_k$	minimum purchase order from supplier $k \in K$
$(T\tilde{C}C)_{jcm}$	unit cost of transportation from customer zone $c \in C$ to collection center $m \in M$ for product $j \in J$
$(T\tilde{C}D)_{jmn}$ center	unit cost of transportation from collection center $m \in M$ to disassembly $n \in N$ for product $j \in J$
$(T\tilde{C}R)_{inl}$	unit cost of transportation from disassembly center $n \in N$ to refurbishing center $l \in L$ for part $i \in I$

$(T\tilde{C}P)_{il}$	unit cost of transportation from refurbishing center $l \in L$ to plant for part $i \in I$
$(T\tilde{C}U)_{jm}$	unit cost of transportation from collection/repair center $m \in M$ to distributor for product $j \in J$
$(ETC)_{jcm}$	environmental impact of transportation from customer zone $c \in C$ to collection center $m \in M$ for product $j \in J$
$(ETD)_{jmn}$	environmental impact of transportation from collection center $m \in M$ to disassembly center $n \in N$ for product $j \in J$
$(ETR)_{inl}$	environmental impact of transportation from disassembly center $n \in N$ to refurbishing center $l \in L$ for part $i \in I$
$(ETR)_{il}$	environmental impact of transportation from refurbishing center $l \in L$ to manufacturing plant for part $i \in I$
$\tilde{\eta}_j$	maximum percentage of product $j \in J$ collected
$\tilde{\gamma}_j$	maximum percentage of product $j \in J$ reused
$\tilde{\lambda}_i$	maximum percentage of part $i \in I$ refurbished
$\tilde{\beta}_i$	maximum percentage of part $i \in I$ recycled

The symbols with a tilde (~) at the top indicate the parameters with uncertainty and are estimated with triangular fuzzy numbers (TFN's). The main advantage of the TFN's is the simplicity and flexibility of the fuzzy arithmetic operations (Lai and Hwang 1992; Zimmermann 2001) and are discussed in the previous chapter (Section 3.2.4).

4.3.1 Objective functions

The proposed model considers two conflicting objectives: (i) maximization of total profit wherein the social factor is also integrated and (ii) minimization of environmental impact.

First objective: Maximizing the total profit

The first objective function is to maximize the economical and social factors in term total profit to the organization (Equation 4.1). The first two terms of the objective function show the profit earned by selling the products (manufactured products and reused products) and profit from recyclers respectively. The third term represents the purchasing cost of parts from external suppliers. The next three terms represent the processing cost, set-up cost and repair cost respectively at the collection/repair center. The next two terms represent the processing and set-up cost at disassembly centres and next two represent the processing and set-up cost at refurbishing centers. The refund to customers and waste disposal cost are represented in the next two terms respectively. The transportation cost from the various facility centers is represented in the last five terms.

$$\begin{aligned}
&Maximize\ \ Z_1 = \\
&\sum_{j}(\widetilde{PF}_j)*(P_j+\sum_{m}A_{jm})+\sum_{n}\sum_{i}(\widetilde{RP})_i*Y_{in}-\sum_{k}\sum_{i}(\widetilde{PC})_{ik}*S_{ik}-\sum_{j}\sum_{c}\sum_{m}(\widetilde{CC})_{jm}*C_{jcm} \\
&-\sum_{m}\sum_{j}(\widetilde{SC})_{jm}*B_{jm}-\sum_{m}\sum_{j}(\widetilde{UC})_{jm}*A_{jm}-\sum_{n}\sum_{i}(\widetilde{DC})_{in}*T_{in}-\sum_{n}\sum_{j}(\widetilde{SD})_{jn}*V_{jn} \\
&-\sum_{l}\sum_{i}(\widetilde{RC})_{il}*F_{il}-\sum_{l}\sum_{i}(\widetilde{SR})_{il}*U_{il}-\sum_{n}\sum_{i}(\widetilde{WDC})_i*W_{in}-\sum_{j}\sum_{m}\sum_{c}(\widetilde{RF})_{jm}C_{jcm} \qquad (4.1) \\
&-\sum_{j}\sum_{c}\sum_{m}(\widetilde{TCC})_{jcm}*C_{jcm}-\sum_{j}\sum_{m}\sum_{n}(\widetilde{TCD})_{jmn}*R_{jmn}-\sum_{i}\sum_{n}\sum_{l}(\widetilde{TCR})_{inl}*F_{inl} \\
&-\sum_{i}\sum_{l}(\widetilde{TCP})_{il}*F_{il}-\sum_{j}\sum_{m}(\widetilde{TCU})_{jm}*A_{jm}
\end{aligned}$$

Second objective: Minimizing the environmental impact

The second objective is to minimize the environmental effect of transportation in the reverse supply chain in terms of carbon footprints (Equation 4.2). The following terms represent the carbon footprints from customer zone to collection center, from collection center to disassembly center, from disassembly center to refurbishing center and refurbishing center to plant respectively. Eco-invent 2.2 is used to calculate the carbon footprints with units of Kg of CO_2/tKm.

$$\begin{aligned}
&Minimize\ Z_2 = \\
&\sum_{j}\sum_{c}\sum_{m}(ETC)_{jcm}*C_{jcm}+\sum_{j}\sum_{m}\sum_{n}(ETD)_{jmn}*R_{jmn}+\sum_{i}\sum_{n}\sum_{l}(ETR)_{inl}*F_{inl} \qquad (4.2) \\
&+\sum_{i}\sum_{l}(ETP)_{il}*F_{il}
\end{aligned}$$

4.3.2 Subject to constraints

Following are the constraints to above mentioned objective functions.

Constraint 4.3 ensures that demand for each product is satisfied with the sum of newly produced products and reused products. Constraints (4.4), (4.5) and (4.6) represent the flow balance constraints at collection centers, disassembly centers and refurbishing centers respectively. While constraints (4.7), (4.8) and (4.9) calculate the number of parts at disassembly centers, number of parts at refurbishing centers and number of products at disassembly centers respectively. Constraint (4.10) calculates the number of products at each collection center from various customer zones. Constraints (4.11), (4.12), (4.13), and (4.14) provide the maximum limit on the number of products collected, number of products reused, number of parts refurbished and number of parts to be recycled respectively. Constraints (4.15), (4.16), (4.17) and (4.18) ensure the capacity limit for collection centers, disassembly centers, refurbishing centers and plant respectively. Constraint (4.19) ensures the maximum and minimum capacity of the external suppliers. Constraints (4.20) and (4.21) are related to binary and general integer values of the decision variables. All the decision variables are positive numbers.

$$\tilde{D}_j = P_j + \sum_m A_{jm} \qquad \forall j \tag{4.3}$$

$$C_{jm} = A_{jm} + \sum_n R_{jmn} \qquad \forall j, m \tag{4.4}$$

$$T_{in} = Y_{in} + W_{in} + \sum_l F_{inl} \qquad \forall i, n \tag{4.5}$$

$$\sum_j q_{ij} * P_j = \sum_l F_{il} + \sum_k S_{ik} \qquad \forall i \tag{4.6}$$

$$T_{in} = \sum_m \sum_j q_{ij} R_{jmn} \qquad \forall i, n \tag{4.7}$$

$$F_{il} = \sum_n F_{inl} \qquad \forall i, l \tag{4.8}$$

$$R_{jn} = \sum_{m} R_{jmn} \qquad \forall j,n \tag{4.9}$$

$$C_{jm} = \sum_{c} C_{jcm} \qquad \forall\ j,m \tag{4.10}$$

$$\sum_{m} C_{jcm} \le \tilde{\eta}_j * \tilde{D}_{jc} \qquad \forall j,c \tag{4.11}$$

$$A_{jm} \le \tilde{\gamma}_j * C_{jm} \qquad \forall j,m \tag{4.12}$$

$$\sum_{l} F_{inl} \le \tilde{\lambda}_i * T_{in} \qquad \forall i,n \tag{4.13}$$

$$Y_{in} \le \tilde{\beta}_i * T_{in} \qquad \forall i,n \tag{4.14}$$

$$C_{jm} \le (MC)_{jm} * B_{jm} \qquad \forall j,m \tag{4.15}$$

$$\sum_{m} R_{jmn} \le (MD)_{jn} * V_{jn} \qquad \forall j,n \tag{4.16}$$

$$\sum_{n} F_{inl} \le (MR)_{il} * U_{il} \qquad \forall i,l \tag{4.17}$$

$$P_j \le (MP)_j \qquad \forall j \tag{4.18}$$

$$(MNS)_k \le \sum_{i} S_{ik} \le (MXS)_k \qquad \forall k \tag{4.19}$$

$$B_{jm}, V_{jn}, U_{il} \quad \in \{0,1\} \qquad \forall i, j, m, n, l \tag{4.20}$$

$$P_j, C_{jcm}, A_{jm}, R_{jmn}, R_{jn}, S_{ik}, T_{in}, F_{inl}, F_{il}, W_{in}, Y_{in} \quad \in I \qquad \forall i, j, m, n, l, k \tag{4.21}$$

4.4. Classification of Multi-objective Solution Methodologies

To solve the multi-objective models different approaches have been proposed in the literature. Hwang and Masud (1979) classified multi-objective solution methodologies into the following three categories (based on the phase in which the decision maker is involved in the decision making process).

Priori method: In priori method the decision maker (DM) expresses preferences before the solution process, e.g. setting goals or weights for the objective functions. The criticism about the priori methods is that it is very difficult for the decision maker to know the preferences beforehand and to be able to accurately quantify (either by means of goals or weights) preferences.

Interactive method: In interactive method, phases of dialogue with the decision maker are interchanged during calculation phases, and the process usually converges after a few iterations to the most preferred solution. The decision maker progressively drives the search with the answers towards the most preferred solution. The drawback is that DM never sees the whole picture (the Pareto set). Hence, the most preferred solution is ‘‘most preferred” in relation to what the DM has seen and compared so far.

Posteriori (or generation) method: In the posteriori (or generation) method all the efficient solutions of the problem (or a sufficient representation) are generated and then the decision maker is involved to select the most preferred solution. The generation methods are usually less popular due to their computational effort (the calculation of the efficient solutions is usually a time consuming process) and the lack of softwares. Weighted sum method and the ε-constraint method are the most widely used generation methods.

The *ε-constraint* method has several advantages over the weighting method (Mavrotas 2009):

(i) Weighting method generates only efficient extreme solutions as it is applied to the original feasible region and results in a corner solution. On the contrary, the ε-constraint method alters the original feasible region and is able to produce non-extreme efficient solutions. Weighting method may spend a lot of runs with different combination of weights resulting in the same efficient extreme solution. On the other hand, the ε-constraint exploits almost every run to produce a different efficient solution thus obtaining a richer representation of the efficient sets.

(ii) The weighting method cannot produce unsupported efficient solutions in multi-objective integer and mixed integer programming problems, while the ε-constraint method does not suffer from this pitfall (Steuer 1989).

(iii) In the weighting method the scaling of the objective functions has strong influence in the obtained results. Therefore, the objective function needs to be scaled to a common scale before forming the weighted sum. In the ε-constrained method this is not necessary.

(iv) An additional advantage of the ε-constraint method is that it can control the number of generated efficient solutions by properly adjusting the number of grid points in each objective function range. This is not so easy with the weighting method.

However, despite its advantages over the weighting method, the *ε*-constraint method has following points that need attention in its implementation:

(i) The calculation of the range of the objective functions over the efficient set.

(ii) The value of epsilon(s), i.e., the right hand side of ε-constraints should be systemically varied in the range of each objective function to generate different Pareto optimal solutions.

(iii) The increased solution time for problems with several (more than two) objective functions.

4.5. The Proposed Solution Methodology

An interactive *ε*-constraint method is used in the proposed model because of the advantages as mentioned above. The steps of the solution methodology are summarized below (Pishvaee and Razmi 2012):

Step 1: Convert the multi-objective fuzzy model into an equivalent crisp model by using the Jiménez *et al.* (2007) method. For this the expected value of imprecise parameters, and the minimum acceptable feasibility degree of decision vector (i.e. α) is determined to convert the fuzzy constraints into the crisp constraints.

Step 2: Determine the α-optimal and α-nadir solutions for each objective function over the efficient set. To calculate the α-optimal solutions – $\left(Z_1^{\alpha-optimal}, x_1^{\alpha-optimal}\right)$ and $\left(Z_2^{\alpha-optimal}, x_2^{\alpha-optimal}\right)$ - the equivalent crisp model is solved for each objective function separately. And then the α-nadir solution for each objective function is estimated as:

$$\begin{aligned} Z_2^{\alpha-nadir} &= \min\left\{ Z_2 \middle| \ Z_1 \geq Z_1^{\alpha-optimal} \ \& \quad x \ \varepsilon \ F(x) \right\} \\ Z_1^{\alpha-nadir} &= \max\left\{ Z_1 \middle| \ Z_2 \leq Z_2^{\alpha-optimal} \ \& \quad x \ \varepsilon \ F(x) \right\} \end{aligned}$$

where, F(x) represents the feasible region involving the constraints of equivalent crisp model.

Step 3: Determine a linear membership function for each objective function as:

$$\mu_1(x) = \begin{cases} 1 & \text{if } Z_1 > Z_1^{\alpha-optimal} \\ \dfrac{Z_1 - Z_1^{\alpha-nadir}}{Z_1^{\alpha-optimal} - Z_1^{\alpha-nadir}} & \text{if } Z_1^{\alpha-nadir} \leq Z_1 \leq Z_1^{\alpha-optimal} \\ 0 & \text{if } Z_1 < Z_1^{\alpha-nadir} \end{cases}$$

$$\mu_2(x) = \begin{cases} 1 & \text{if } Z_2 < Z_2^{\alpha-optimal} \\ \dfrac{Z_2^{\alpha-nadir} - Z_2}{Z_2^{\alpha-nadir} - Z_2^{\alpha-optimal}} & \text{if } Z_2^{\alpha-optimal} \leq Z_2 \leq Z_2^{\alpha-nadir} \\ 0 & \text{if } Z_2 > Z_2^{\alpha-nadir} \end{cases}$$

where $\mu_1(x)$ and $\mu_2(x)$ represent the degree of satisfaction for the first and second objective functions respectively.

Step 4: Convert the equivalent multi-objective crisp model into a single-objective model based on ε-constraint method as:

$$\begin{aligned} &\max \mu_1(x) \\ &st\ \mu_2(x) \geq \varepsilon, \\ &x \in F(x), \\ &\varepsilon \in [0,1] \end{aligned}$$

In this formulation, satisfaction degree of first objective function is kept in the objective function and the satisfaction degree of second objective function is used as a side constraint. However, any one of the satisfaction degrees can be used as a side constraint or objective function.

Step 5: Vary the value of epsilon systemically between 0 and 1 to generate different Pareto-optimal solutions over the whole efficient set.

Step 6: If the decision maker is satisfied with one of the generated solutions, stop and select the preferred solution as the final decision, otherwise select the most preferred segment and go to step 5 to vary the value of ε in the new range and generate new Pareto-optimal solutions. Also, in some cases, decision maker may be interested to change the value of α and if the value of α is changed the algorithm should restart from step 1.

4.6. Illustrative Example

In this section a numerical example is presented to illustrate how the proposed multi-objective model works in a multi-product, multi-echelon CLSC framework under uncertain environment. A data set is prepared reflecting the real business situation. It is assumed that there are two types of products and three types of parts. The weights of each product, part and utilization factor are shown in Table 4.1. It is assumed that there are three collection/repair centers, two disassembly centers, two refurbishing centers, three external suppliers, one recycle center, and one disposal center. The transportation cost from customer zones to collection centers and from refurbishing centers to plant is given in Table 4.2 and Table 4.3 respectively. The transportation distance of collection centers from customer zones, distributor and disassembly centers is given in Table 4.4. Table 4.5 provides the distance of refurbishing centers from plant. The maximum capacity of collection centers and disassembly centers is given in Table 4.6. Table 4.7 provides the maximum capacity of refurbishing centers. The maximum purchase order for suppliers 1, 2 and 3 are 4000, 5000 and 5000 respectively, and the minimum purchase order for each supplier is 100. It is further assumed that $\tilde{\eta}_j$ (maximum percentage of product *j* collected) = (0.50, 0.60, 0.70), $\tilde{\gamma}_j$ (maximum percentage of product *j* reused) = (0.10, 0.20, 0.30), $\tilde{\lambda}_i$ (maximum percentage of part *i* refurbished) = (0.65, 0.70, 0.75), and $\tilde{\beta}_i$ (maximum percentage of part *i* recycled) = (0.10, 0.15, 0.20). The values of rest input parameters are taken from the illustrative example in section 3.5 of the last chapter

Table 4.1: Weight of each product, part and utilization factor

q_{ij}	***i*=1**	***i*=2**	***i*=3**	**Weight of product**
j=1	2	3	2	72
j=2	3	3	2	82
Weight of part	10	12	8	

Table 4.2: The transportation cost (per km) from customer zone (*c*) to collection center (*m*) for each product (*j*)

	$(T\tilde{C}C)_{jcm}$ **(*j*=1)**			$(T\tilde{C}C)_{jcm}$ **(*j*=2)**		
	m = 1	*m* = 2	*m* = 3	*m* = 1	*m* = 2	*m* = 3
c = 1	(0.4,0.5,0.6)	(0.5,0.6,0.7)	(0.7,0.8,0.9)	(0.4,0.5,0.6)	(0.5,0.6,0.7)	(0.7,0.8,0.9)
c = 2	(0.4,0.5,0.6)	(0.4,0.5,0.6)	(0.6,0.7,0.8)	(0.4,0.5,0.6)	(0.4,0.5,0.6)	(0.6,0.7,0.8)
c = 3	(0.3,0.4,0.5)	(0.5,0.6,0.7)	(0.7,0.8,0.9)	(0.3,0.4,0.5)	(0.5,0.6,0.7)	(0.7,0.8,0.9)

Table 4.3 The transportation cost (per km) from refurbishing center (*l*) to plant for each part (*i*)

$(T\tilde{C}P)_{il}$	***i*=1**	***i*=2**	***i*=3**
l=1	(0.2,0.3,0.4)	(0.4,0.5,0.6)	(0.5,0.6,0.7)
l=2	(0.3,0.4,0.5)	(0.3,0.4,0.5)	(0.4,0.5,0.6)

Table 4.4 The transportation distance (km) of customer zone (*c*), disassembly center (*n*) and distributor from collection center (*m*)

Distance	**c = 1**	**c = 2**	**c = 3**	**n = 1**	**n = 2**	**Distributor**
m = 1	3	4	5	20	20	3
m = 2	4	2	4	18	22	2
m = 3	6	5	3	25	15	5

Table 4.5 The transportation distance (km) of disassembly center (*n*) and plant from refurbishing center (*l*)

Distance	**n = 1**	**n = 2**	**Plant**
l = 1	10	12	6
l = 2	10	8	8

Table 4.6 Maximum capacity at collection centers (*m*) and disassembly centers (n) for each product (*j*)

Capacity	$(MC)_{jm}$			$(MD)_{jn}$	
	$m = 1$	$m = 2$	$m = 3$	$n = 1$	$n = 2$
$j = 1$	600	800	600	1000	1000
$j = 2$	700	600	600	1000	800

Table 4.7 Maximum capacity at refurbishing center (*l*) for each part (*i*)

Capacity	$(MD)_{il}$	
	$l = 1$	$l = 2$
$i = 1$	1500	1800
$i = 2$	2000	1800
$i = 3$	1500	1000

To analyze the performance of the proposed model, the model is coded and solved using LINGO 14.0 optimization software. In the present case, the satisfaction degree of economic objective is kept in the model objective function and the satisfaction degree of environmental objective is used as a side constraint. Pareto-optimal solutions are generated using the modified ε-constraint method at feasibility degrees 0.5 (i.e., α-level = 0.5).

4.7. Results and Discussion

The results (Table 4.8) confirm that the two objective functions (i.e., maximization of total profit and minimization of environmental impact) are in conflict with each other. As the decrease in environmental impact leads to an increase in total cost and therefore decreases the profit of the organization. The last column of Table 4.8 shows the price paid for environmental protection, i.e. loss in economical profit of the organization to take care for environmental protection. This indicator has twofold importance, i.e. (i) it can be used as a quantitative indicator by organizations to show their efforts to stakeholders in protecting the environment, and (ii) it can be considered as a baseline by government to regulate the incentive to organizations (Pishvaee and Razmi 2012).

The decision maker can adjust the values of epsilon between 0 and 1. Therefore, initially decision maker starts with a coarse range to quickly cover the whole range of Pareto-optimal solutions. However, at later iterations the decision maker may be interested in selecting the final preferred solution through a fine tuning using a denser grid. In the present case, an initial solution set is generated using ε = [0,1] with an increment of 0.2 as shown in Table 4.8. The results (Table 4.8) show that with the increase in degree of satisfaction of environmental objection function, the degree of satisfaction of economical objective function decreases.

Table 4.8 Summary of results for first iteration at α =0.5 and ε = [0, 1]

$\mu(Z_2)$	$\mu(Z_1)$	**Z_1 (Eco.)**	**Z_2 (Env.)**	**Price for Environmental Protection**
0	0.9999	252026.8	518.126	~ 0
0.2	0.9929	251937.5	475.699	89.3
0.4	0.9480	251371.7	433.272	655.1
0.6	0.8771	250477.8	390.845	1549
0.8	0.7733	249168.9	348.418	2857.9
0.9999	0.0033	239417.0	305.991	12609.8

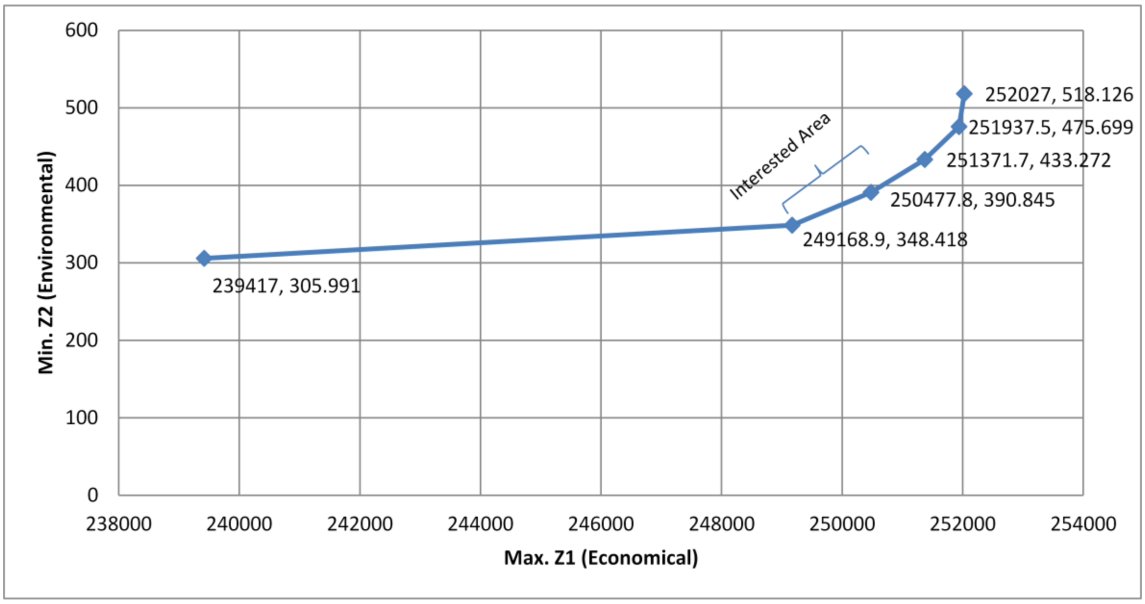

Figure 4.2: Graphical representation of iterative solution at most preferred point for iteration 1

Table 4.9 Summary of results for second iteration for ε = [0.6, 0.8]

$\mu(Z_2)$	$\mu(Z_1)$	**Z_1 (Eco.)**	**Z_2 (Env.)**	**Price for Environmental Protection**
0.60	0.877141	250477.8	390.845	00
0.62	0.869307	250379	386.6023	98.8
0.64	0.861406	250279.3	382.3596	198.5
0.66	0.854078	250186.9	378.1169	290.9
0.68	0.845493	250078.7	373.8742	399.1
0.70	0.840362	250014	369.6315	463.8
0.72	0.831346	249900	365.3888	577.8
0.74	0.820931	249678.9	361.1416	798.9
0.76	0.813429	249674.3	356.9034	803.5
0.78	0.796454	249460.3	352.6607	1017.5
0.80	0.773346	249168.9	348.418	1308.9

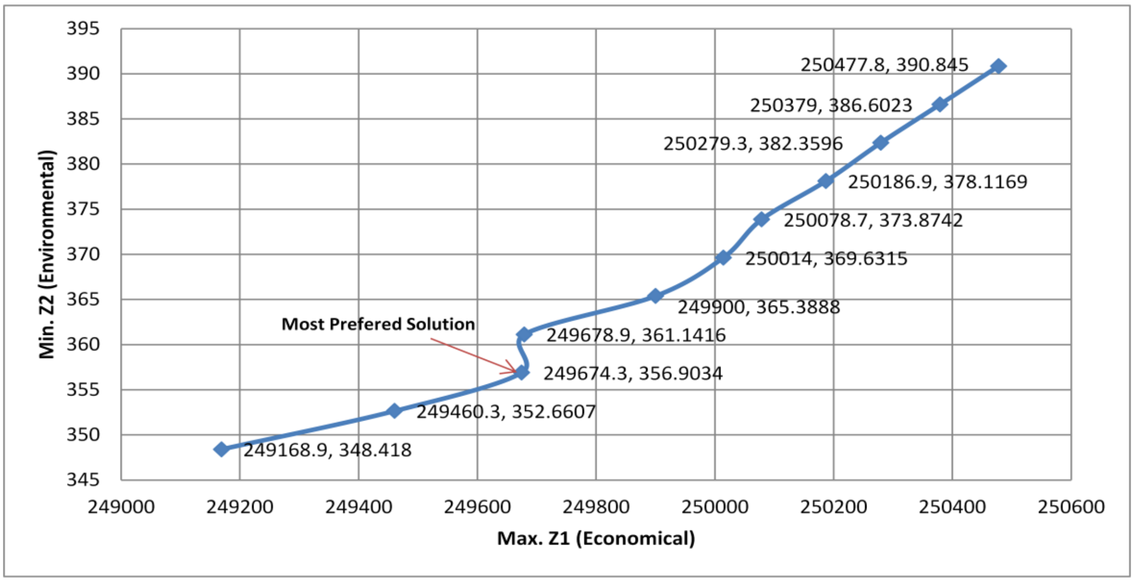

Figure 4.3: Graphical representation of iterative solution at most preferred point for iteration 2

Table 4.10 Number of parts purchased from external supplier (S_{ik}), number of parts disassembled (T_{in}), number of parts refurbished (F_{il}), number of parts recycled (Y_{in}) and number of parts disposed (W_{in}) at most preferred point

	S_{ik}			T_{in}		F_{il}		W_{in}		Y_{in}	
	$k = 1$	$k = 2$	$k = 3$	$n = 1$	$n = 2$	$l = 1$	$l = 2$	$n = 1$	$n = 2$	$n = 1$	$n = 2$
$i = 1$	4000	293	0	1680	1380	1500	642	252	207	252	207
$i = 2$	0	793	5000	1680	1380	342	1800	252	207	252	207
$i = 3$	0	3862	0	1120	920	428	1000	168	138	168	138

Table 4.11 Number of parts purchased from external supplier (S_{ik}), number of parts disassembled (T_{in}), number of parts refurbished (F_{il}), number of parts recycled (Y_{in}) and number of parts disposed (W_{in}) at $\mu(Z_2 = 0)$

	S_{ik}			T_{in}		F_{il}		W_{in}		Y_{in}	
	$k = 1$	$k = 2$	$k = 3$	$n = 1$	$n = 2$	$l = 1$	$l = 2$	$n = 1$	$n = 2$	$n = 1$	$n = 2$
$i = 1$	3590	0	0	1680	2120	1500	1160	252	318	252	318
$i = 2$	0	0	4767	1680	2460	1098	1800	252	369	252	369
$i = 3$	0	3178	0	112	1640	932	1000	168	246	168	246

Table 4.12 Number of parts purchased from external supplier (S_{ik}), number of parts disassembled (T_{in}), number of parts refurbished (F_{il}), number of parts recycled (Y_{in}) and number of parts disposed (W_{in}) at $\mu(Z_2 = 0.9999)$

	S_{ik}			T_{in}		F_{il}		W_{in}		Y_{in}	
	$k = 1$	$k = 2$	$k = 3$	$n = 1$	$n = 2$	$l = 1$	$l = 2$	$n = 1$	$n = 2$	$n = 1$	$n = 2$
$i = 1$	4000	324	0	1680	1348	1176	943	252	203	252	202
$i = 2$	0	806	5000	1680	1368	1175	957	253	206	252	205
$i = 3$	0	3870	0	1120	912	777	645	168	138	168	136

Figure 4.2 shows these results graphically that with the increase in economical objective function, the environmental impact also increases. As the DM is interested in the maximization of profit as well as minimization of environmental impact, so the area of interest is the curved portion, i.e. when the value of $\mu(Z_2)$ lies between 0.6 and 0.8. To refine the results in the second iteration new Pareto-optimal solutions are generated using an increment of 0.02 between 0.6 and 0.8 (as an interesting area) and the results are shown in Table 4.9. Figure 4.3 represents these results graphically. Finally, based on firm's preferences the decision maker selected Z_1 = 249674.3 (the maximum of economical objective) and Z_2 = 356.9034 (the minimum of environmental objective) as the final preferred solution with $\mu(Z_1) = 0.8134$ and $\mu(Z_2) = 0.76$. Further, at this point the numbers of parts to be purchased, number of parts to be refurbished, numbers of parts to be disposed and number of parts to be recycled are shown in Table 4.10. Table 4.11 and 4.12 shows all the decision variable when the degree of satisfaction of environmental objective function is 0 and 1 respectively. In other words, when the environmental objective function weight is zero, the results (Table 4.11) are different than the preferred solution considering all criteria. Similarly, if the economic objective function weight is zero, the results (Table 4.12) are different. The results help the top management in taking a decision if a fixed carbon footprint (kg CO_2-eq) is desired than what will be the

decrease in profit for it and vice-versa. The results also help the organization in finding the optimum location and allocation of facility centers, optimum number parts to be purchased from external supplier to fulfill the customer demand after considering the parts from reverse supply chain.

4.8. Summary

With the increasing concern for sustainability, the network design and optimization of single objective closed-loop supply chain was not sufficient, therefore this chapter provided a multi-objective closed-loop supply chain network design and optimization considering the economical and environmental factors. The first objective is to maximize the profit of the organization by optimally deciding the number of products to be remanufactured and number of parts to be purchased from external suppliers along with location and allocation of different facility centers, while the second objective is to minimize the environmental impact in terms of carbon footprints (with units of Kg of CO_2/tKm) of the reverse supply chain transportation. In the proposed framework incentive to customer is considered as the social factor and is merged with economical objective function.

The model considers multi-customer zones, multi-collection centers, multi-disassembly centers, multi-refurbishing centers, and multi-external suppliers to take care of purchasing cost, transportation cost, processing cost, set-up cost, and capacity constraints simultaneously. The uncertainties related to ill-known parameters are represented by triangular fuzzy numbers. A fuzzy mixed integer linear programming model is proposed to represent the proposed framework in mathematical terms for optimization.

Because of the advantages of interactive ε-constraint method, it has been used to calculate the Pareto optimal solutions for different degrees of satisfaction of the environmental objective function. It has also been observed that the increase in degree of satisfaction of environmental objective function leads to decrease in degree of satisfaction of economical objective. It is also observed that the values of objective function and decision variables change with the change in degree of satisfaction of environmental objective function. Therefore, the most preferred or the balanced solution is the corner point solution as shown in Figure 4.3. The effectiveness of the developed fuzzy optimization model as well as the usefulness of the proposed solution approach is investigated by solving an illustrative example using LINGO 14.0 optimization.

CHAPTER 5

ASSESSMENT AND EVALUATION OF COLLECTION METHODS IN REVERSE LOGISTICS

This chapter aims at providing a multi-criteria decision model for the assessment and evaluation of different collection methods in reverse logistics under uncertain environment. An integrated fuzzy multi-criteria decision model has been developed for the evaluation of different collection methods. The evaluation has been done based on the criteria of initial investment, value added recovery, return volume, operating cost, degree of supply chain control, and level of customer satisfaction. The three alternatives selected in the study are collection directly by the manufacturer from the customer, collection by the retailer and collection by the third party. Fuzzy mathematics is used to take care of uncertainties in the reverse logistics. The utility of the proposed evaluation methodology has been validated by solving a case example from Indian automotive sector.

5.1. Introduction

Collection is the first and an important element of the reveres logistics (Wojanowski *et al.*, 2007). It refers to all activities rendering used products available and physically moving them to some point where further treatment is conducted for product recovery (Sasikumar and Kannan, 2008). Collection activities are critical in determining the economic viability of the entire recovery chain, as the efficiency and effectiveness of reverse logistics greatly dependents on method of collection. In real time situations, the collection of end-of-life/end-of-use products from the customer and their return to the manufacturer is tedious and time consuming. Sometimes actual recovery process may be economically viable but not the entire business, due to collection costs. This makes collection as a crucial link in the recovery chain (Goggin *et al.*, 2000). Collection can be of two types – collection of products or collection of packages. In this chapter collection refers to the collection of products.

Majority of the research on collection in reverse logistics is related to location-allocation of collection centers or the selection of third party logistic providers. There is little work on the assessment and selection of the collection method, i.e. how the actual collection should be done? Should it be done by original equipment manufacturer (OEM) directly or with an incentive to retailers or by the third part logistics providers? The evaluation of collection method depends on many potential criteria such as, initial investment, value added recovery, volume of return, operating cost, level of customer satisfaction, etc (Barker and Zabinsky, 2008; Lambert *et al.*, 2011; Savaskan *et al.*, 2004; Serrato *et al.*, 2007). Therefore, the assessment and evaluation of collection method is a multi-criteria decision making problem.

This chapter proposed an integrated fuzzy analytical hierarchical process (Fuzzy AHP) and fuzzy technique for order preference by similarity to ideal solution (Fuzzy TOPSIS) for the evaluation of best collection method. With the integration of Fuzzy AHP and Fuzzy TOPSIS, the proposed methodology will have the advantages of both (Perçin, 2009). Fuzzy AHP is used to calculate the criteria weight and Fuzzy TOPSIS is used to find the ranking of alternative collection methods using linguistic variables. Fuzzy mathematics is used to handle the uncertainty in RL as discussed in Section 3.2. It is expected that the proposed model will provide the decision makers/managers sufficient confidence for selecting the best collection method under the given circumstances.

5.2. Model Development

Collection is an important activity in reverse logistics and in current practice, there exist a variety of channels to collect the returned products. As discussed in the literature review chapter (section 2.3.1) these can be broadly classified into three methods, i.e. collection directly by the original equipment manufacturer, collection by retailers and collection by third party logistics providers (Das and Chowdhury, 2012; Lambert *et al.*, 2011; Savaskan *et al.*, 2004).

5.2.1 Alternative collection methods in reverse logistics

(i) Collection directly by original equipment manufacturer

In some cases, manufacturers collect their used products directly from the customers. For instance, Xerox Corporation collected the end of lease copiers under the green remanufacturing program that saved 40%–65% of the manufacturing costs through the reuse of parts and materials (Ginsburg, 2001). Similar activities are undertaken by Hewlett Packard Corporation for computers and peripherals and by Canon for print and copy cartridges.

(ii) Collection by retailers

Manufacturers of consumer products such as single-use cameras and mobile phones utilize retailers for collecting their used products. For instance, Eastman Kodak Company receives single-use cameras from large retailers. Wojanowski *et al*. (2007) proposed the collection of products from households using retailers under a deposit-refund scheme. They presented a continuous modeling framework for designing a drop-off facility network and determining the sales price that maximize the firm’s profit under a given deposit-refund. The customers preferences with regards to purchasing and returning the product are incorporated via a discrete choice model with stochastic utilities. Das and Chowdhury (2012) also proposed to involve retail outlets for the collection of returned products through cost-benefit based agreements. This approach motivates the retailer by taking promotional steps that would ensure the collection of returned products. They proposed a mixed integer programming (MIP) model for integrated reverse logistics with modular product design to maximize profit by considering the collection of returned products.

(iii) Collection by third party logistics providers

In some industries, independent third parties are handling used-product collection for the original equipment manufacturers (OEMs). Krumwiede and Sheu (2002) developed an RL decision-making model to guide the process of examining the feasibility of implementing RL with third-party providers such as transportation companies. The model is based on literature review and interviews with five logistics managers at prominent third-party logistics companies headquartered in the United States. Schultmann *et al.* (2006) modeled RL problems for automobile industries, specifically for end-of-life vehicles in German closed-loop supply chains. Their study used third party collection centers and evaluated network design concepts for separating and reprocessing plastic end-of-life vehicle components. Cruz-Rivera and Ertel (2009) studied the RL for end-of-life vehicles (ELVs) in Mexico using third party collection centers in an un-capacitated facility location problem. Mahmoudzadeh *et al.* (2013) developed a third party logistics network for ELVs in Iran.

5.2.2 Criteria for the assessment of collection methods

Each and every collection method has its own advantages and disadvantages. Collection by OEM is preferred for high value added products and it helps the OEM to have better control over the supply chain and aftermarket protection. Collection by manufacturer also provides a high level of customer service/satisfaction. It helps to reduce the volume of products to be transported to the company as most of the technical problems will be solved at the service point itself. But it requires high initial investment as compared to the other two alternatives. Collection by contracting to retailers can be used for low to medium value products and it may be economical compared with collection by manufacturer directly. It simplifies the collection work of manufacturers but the level of customer satisfaction will be less and the volume of transportation will be more. Initial investment will be least when the collection is done through the retailers. The third party collection can be used if product variety is high and it helps to reduce the complexity of existing supply chain. But the degree of control is less as compared to collection by OEM. Third party logistic provider takes the advantage of economy of scale and may pass a part of it to the manufacturer. From the literature review it is identified that the selection and evaluation of collection methods depends on initial investment, value added recovery, volume of return, operating cost, and level of customer service/satisfaction (Barker and Zabinsky, 2008; Dowlatshahi, 2009; Lambert *et al.*, 2011; Savaskan *et al.*, 2004). A brief description of these six criteria is given below:

(i) Initial investment

Initial investment is an important criterion for reverse logistics implementation. Initial investment includes fixed and set-up cost for facility centers and the other infrastructure. Information and technological systems require more funds because without these the return product tracking, tracing and product recovery is not possible in the present environment (Ravi and Shankar, 2005). However, this requires financial support. Therefore, with respect to initial investment collection through retailers or third party logistics providers are better methods.

(ii) Value added recovery

A reverse logistics program can bring cost benefits to the companies by emphasizing on resource reduction, adding value from the recovery of products, or reducing the disposal costs (Fen, 2012; Kannan and Sasi Kumar, 2009; Ravi *et al.*, 2005; Stock, 1998). Recovery of products for remanufacturing, repair, reconfiguration, and recycling can create profitable business opportunities (Giuntini and Andel, 1995). Kim *et al.* (2008) in their case study of automotive alternators, found that a remanufactured alternator uses less than 20% of the materials, 16% of the energy and releases 35% of the greenhouse gas emissions of those released in the process of producing a new product.

(iii) Operating cost

Reverse logistics include many costs like collection cost, disassembly cost, remanufacturing cost, disposal cost, transportation cost, and inventory cost. Cost of collection is an important part in the product recovery management (Goggin *et al.*, 2000). The operational cost for collection includes transportation cost, inventory cost, cost of manpower and energy required. The training of personnel related to the reverse logistics is also very important for efficiently managing and eventually making the reverse logistics profitable. It also includes the incentive that the organization is paying to the retailers or third party logistics providers for the collection of returned products.

(iv) Return volume

Volume of returned products is an important factor in deciding the collection method. High variability in return volume reduces the economic feasibility of maintaining a firm’s own RL facilities because the required capacity will be changing constantly. It is suggested that under these circumstances third party logistics provider is the better alternative as they can have the advantage of economy of scale through consolidation (Meade and Sarkis, 2002; Serrato *et al.*, 2007). If the return volume is high, its better to do the collection and reverse logistics practices by the OEM itself. Whereas the medium rate of return can be handled with an incentive to retailer for collection of returned products.

(v) Degree of supply chain control

Supply chain control is an important factor in the profit and success of any organization. It includes how, what and when to collect the return or end-of-life products. Supply chain control also includes the timely delivery of products so that the maximum value can be recovered from the returned products. Timely delivery is especially important when the product is retuned under warranty/service. Degree of supply chain control will be different in different network configurations. A manufacture can have the best control on its supply chain when the collection and other activities are done by OEM itself and the least one when it's offered to third party logistics providers as they may also have their own constrains.

(vi) Level of customer satisfaction

Customer relationship and satisfaction is essential for the success of a business in this competitive world (Fen, 2012). It offers an opportunity to the companies to differentiate or distinguish themselves with customers (Autry *et al.*, 2001; Daugherty *et al.*, 2005). A well designed reverse logistics system can promote long-term relationships (Daugherty *et al.*, 2002). Handing of returns by organization is often evaluated by customers as an important factor for future purchase and satisfaction. It is always desired by the customers that OEM should handle product return for better quality or service.

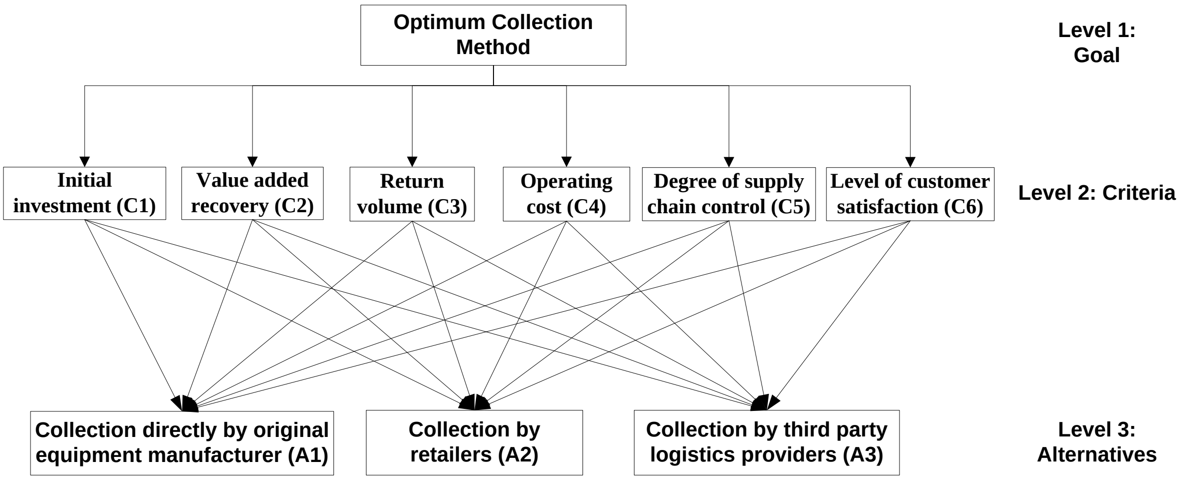

Figure 5.1 Hierarchy for the selection of collection method in reverse logistics

Based on the above discussion it is comes out that there are three alternative collection methods (i.e. collection directly by original equipment manufacturer, collection with retailers and collection by third party logistics providers) which are to be evaluated based on the six criteria –initial investment, value added recovery, operating cost, return volume, degree of supply chain control, and level of customer satisfaction). The situation is depicted as a MCDM problem in Figure 5.1.

5.3. Background of AHP and TOPSIS

The following are the key points of analytical hierarchy process (AHP) and Technique for order preference by similarity to ideal situation (TOPSIS) that justifies the selection of integrated AHP and TOPSIS for the present problem.

5.3.1 Features and applications of AHP

The analytical hierarchy process (AHP), first introduced by Saaty (1980), is an effective method for solving multi criteria decision problems. It is also known as an eigenvector method. It indicates that the eigenvector corresponding to the largest eigenvalue of the comparisons matrix provides the relative priorities of the factors. The hierarchy of collection method selection needs to be established before performing the pairwise comparison of AHP, as shown in Figure 5.1. After constructing a hierarchy, the decision-maker(s) makes a pairwise comparison of the elements at a given level to estimate their relative importance in relation to the element at the immediate proceeding level. A frequently used scale for this act is the nine-point scale (Saaty, 1994) which shows the judgments or preferences among the options such as equally important, moderately more important, strongly more important, very strongly more important, and extremely more important. Even though the discrete scale of 1–9 has the advantages of simplicity and easiness for use, it does not take into account the uncertainty associated with the mapping of one’s perception or judgment to a number. Moreover the decision makers may be reluctant to provide crisp judgments. Therefore, in this study, a scale containing triangular fuzzy number $\left(\tilde{1}-\tilde{9}\right)$ is used to represent subjective pairwise comparisons of selection process in order to capture the uncertainty and vagueness. The fuzzy approaches allow for a more accurate description of the decision-making process (Chen *et al.*, 2008).

The analytical hierarchy process has been studied extensively in almost all the applications related with multi-criteria decision making. The wide applicability is due to its simplicity, ease of use, and great flexibility (Ho, 2008). One of the major advantages of AHP is that it calculates the inconsistency index as a ratio of the decision maker's inconsistency and randomly generated index. This index is important for the decision maker to assure that judgments were consistent and that the final decision is made well (Pohekar and Ramachandran, 2004).

AHP can be integrated with other techniques like TOPSIS, Data Envelopment Analysis (DEA), Qulaity Function Deployment (QFD), Linear Programming (LP), Mixed-integer Linear Programming (MILP), Genetic Algorithm (GA), Goal Programming (GP) in order to consider both qualitative and quantitative factors (Ho, 2008). Integrated AHP can definitely make a more realistic and promising decision than the stand-alone AHP. Table 5.1 shows a few applications of AHP and fuzzy AHP in supply chain management; while Table 5.2 shows the application of integrated AHP. It is observed that the focus has been confined to the applications of the integrated AHP (i.e. AHP with fuzzy logic, TOPSIS, LP, DEA, GA, GP, etc.) rather than the stand-alone AHP.

Table 5.1 Some applications of AHP and Fuzzy AHP in supply chain management

AHP/ Fuzzy AHP	Author and Year	Objective
AHP	Bayazit (2005)	Decision-making for flexible manufacturing systems
AHP	Bian and Yu (2006)	Analyzed various countries in the Asia pacific region to determine their suitability for carrying out RL operations for an international electrical manufacturer
AHP	Staikos and Rahimifard (2007)	To identify the most appropriate reuse, recovery and recycling option for post-consumer shoes
AHP	Lu *et al.*(2007)	To evaluate the environmental principles applicable to green supplier
AHP	Shi *et al.* (2008)	To examine and prioritize underlying barriers to adoption of cleaner production by SMES in China
AHP	Fernandez and Kekale (2008)	Conceptual model selection in case of reverse logistics
AHP	Barker and Zabinsky (2011)	Multi-criteria decision making model for reverse logistics
AHP	Herrmann *et al.*(2011)	To assess the alternative propulsion systems for vehicles
AHP	Sangwan (2011)	Multi-criteria decision model for justification of green manufacturing systems
AHP	Dey and Cheffi (2012)	Green supply chain performance measurement
AHP	Akdoğan and Coşkun (2012)	To calculate the weight of drivers for reverse logistics
Fuzzy AHP	Noorul Haq and Kannan (2006)	Evaluating and selecting a vendor in a supply chain model
Fuzzy AHP	Lu *et al.* (2007)	To evaluate the supplier's performance integrating AHP and fuzzy logic
Fuzzy AHP	Kannan *et al.* (2008a)	Selecting the collecting centre location in the RL supply chain model
Fuzzy AHP	Pochampally and Gupta (2008)	Strategic planning of a reverse supply chain network
Fuzzy AHP	Kannan (2009)	Selecting the best third party reverse logistics provider (3PRLP) for the battery industry
Fuzzy AHP	Govindan and Murugesan (2011)	Selecting the third party logistics provider using fuzzy extent analysis for the case of battery industry
Fuzzy AHP	Cho *et al.*(2012)	Measuring the performance of service supply chain management

Table 5.2 Some application of integrated AHP in supply chain management

Integrated AHP	Author and Year	Objective
AHP + LP	Ghodsypour and O'Brien (1998)	A decision support system for supplier selection
AHP + LP	Kannan *et al.* (2009)	Selecting the best third party logistics providers
AHP + LP	Shaw *et al.*(2012)	Supplier selection using fuzzy AHP and fuzzy multi-objective linear programming for developing low carbon supply chain
AHP + MILP	Korpela *et al.*(2002)	Production capacity allocation and supply chain design
AHP + MILP	Pochampally and Gupta (2003)	Strategic planning of an efficient reverse supply chain network
AHP + GP	Zhou *et al.*(2000)	To evaluate the priorities of goals and weights of deviation variables in supply chain optimization of continuous process industries with sustainability considerations
AHP + GP	Wang *et al.*(2005)	Supplier selection
AHP + GA	Dehghanian and Mansour (2009)	To calculate the social impact in designing sustainable recovery network for EOL products
AHP + GA	Chan and Chung (2004)	Transportation route selection
AHP + QFD	Chuang (2001)	Facility location selection
AHP + DEA	Hadad and Hanani (2011)	Selecting the best alternative
AHP + ISM	Kannan *et al.* (2008b)	Analyzed the interaction of criteria to select the green suppliers
Fuzzy AHP + MDS	Chen *et al.*(2008)	Identifying the preference similarity of alternatives
Fuzzy AHP + PROMETHEE	Avikal *et al.* (2013)	For disassembly line balancing problems

5.3.2 Features and applications of TOPSIS

Technique for order preference by similarity to ideal situation (TOPSIS) method was first proposed by Hwang and Yoon (1981). The basic concept of this method is that the chosen alternative should have the shortest distance from the positive ideal solution (PIS) and the farthest distance from negative ideal solution (NIS). Positive ideal solution is a solution that maximizes the direct criteria and minimizes indirect criteria, whereas the negative ideal solution maximizes the indirect criteria and minimizes the direct criteria

(Wang and Elhag, 2006). TOPSIS simultaneously considers the distances to both PIS and NIS, and a preference order is ranked according to their relative closeness. It is a utility-based method that compares each alternative directly depending on data in the evaluation matrices and weights (Cheng *et al.*, 2002). In the classical TOPSIS method, the weights of the criteria and the ratings of alternatives are known precisely and crisp values are used in the evaluation process. However, under many conditions crisp data are inadequate to model real-life decision problems. Therefore, the fuzzy TOPSIS method is proposed where ratings of alternatives are evaluated by linguistic variables represented by fuzzy numbers to deal with the deficiency in the traditional TOPSIS.

The characteristics of TOPSIS and AHP are compared in Table 5.3 (Shih *et al.*, 2007). The major weakness of TOPSIS is that it does not provide the weight elicitation and consistency check for judgments. However, AHP's employment has been significantly restrained by the human capacity for information processing, and thus the number seven plus or minus two would be the ceiling in comparison (Saaty and Ozdemir, 2003). From this viewpoint, TOPSIS alleviates the requirement of paired comparisons and the capacity limitation might not significantly dominate the process. Hence, it would be suitable for cases with a large number of attributes and alternatives. Olson (2004) reviewed several applications of TOPSIS using different weighting schemes and different distance metrics, and compares results of different sets of weights applied to a previously used set of multiple criteria data. According to the simulation comparison from Zanakis *et al.* (1998), TOPSIS has the fewest rank reversals among the eight methods in the category. Table 5.4 shows some of the application of TOPSIS and Fuzzy TOPSIS in supply chain management.

Table 5.3 Comparison of AHP and TOPSIS

Characteristics	**AHP**	**TOPSIS**
Category	Cardinal information, information on attribute, MADM Cardinal	Cardinal information, information on attribute, MADM Cardinal
Core process	Pairwise comparison	The distances from PIS and NIS
Attribute	Given	Given
Weight elicitation	Pairwise comparison	Given
Consistency check	Provided	None
Number of attributes accommodated	7±2	Many more
Number of alternatives accommodated	7±2	Many more

Table 5.4 Some applications of TOPSIS and Fuzzy TOPSIS in supply chain management

TOPSIS/ Fuzzy TOPSIS	**Author and Year**	**Objective**
TOPSIS	Deng *et al.* (2000)	Inter-company comparison
TOPSIS	Cheng *et al.*(2002)	Using multiple criteria decision analysis for supporting decisions of solid waste management
Fuzzy TOPSIS	Chu (2002)	Facility location selection
Fuzzy TOPSIS	Wang and Elhag (2006)	Application to bridge risk assessment.
Fuzzy TOPSIS	Yang and Hung (2007)	Multiple-attribute decision making methods for plant layout design problem
Fuzzy TOPSIS	Ertuğrul and Karakaşoğlu (2008)	Facility location selection
Fuzzy TOPSIS	Alimoradi *et al.* (2011)	A hybrid model for remanufacturing facility location problem in a closed-loop supply chain
Fuzzy TOPSIS	Awasthi *et al.* (2011)	Location planning for urban distribution centers under uncertainty
Fuzzy TOPSIS	Govindan *et al.* (2013)	For measuring sustainability performance of a supplier based on triple bottom line approach

5.3.3 Advantages and applications of integrated AHP and TOPSIS

Both AHP and TOPSIS have their own advantages. Table 5.5 provides some of applications of integrated AHP and TOPSIS. With the integrated of AHP and TOPSIS methods, evaluation process has advantages of the two methods (Gangurde and Akarte, 2013; Önüt *et al.*, 2008).

Table 5.5 Some of the application of integrated AHP and TOPSIS

AHP+TOPSIS	**Author and Year**	**Objective**
Fuzzy AHP + TOPSIS	Ertuğrul and Karakaşoğlu (2008)	Facility location selection
Fuzzy AHP + TOPSIS	Gumus (2009)	Evaluation of hazardous waste transportation firms
Fuzzy AHP + TOPSIS	Perçin (2009)	Evaluation of third-party logistics (3PL) providers
Fuzzy AHP + TOPSIS	Sun (2010)	A performance evaluation model by integrating fuzzy AHP and fuzzy TOPSIS
AHP + TOPSIS	Pires *et al.* (2011)	Assessment for sustainable expansion of the solid waste management system
AHP + TOPSIS	Ravi (2012)	Selection of third-party reverse logistics providers for End-of-Life computers
Fuzzy AHP + TOPSIS	Samvedi *et al.* (2012)	Quantifying risks in a supply chain
Fuzzy AHP + TOPSIS	Patil and Kant (2014)	Ranking the solutions of knowledge management adoption in supply chain

The following are some key points justifying the advantage of integrated AHP with TOPSIS.

- AHP helps to decompose an unstructured problem into a reliable hierarchic structure that includes various criteria, sub-criteria, and alternatives to determine the best choice.
- AHP can elicit judgments from decision makers to determine weights of the elements.
- One of the major advantages of AHP is that it calculates the inconsistency index which is important for the decision maker to assure that the judgments were consistent and that the final decision is made well.

- Large number of pairwise comparisons performed by decision makers can cause usage of the AHP process impractical.
- TOPSIS technique can be used to reduce the number of pairwise comparisons and to rank the alternatives.
- TOPSIS method is rational, understandable, and easily programmable computation procedure.
- TOPSIS is proved to be one of the best methods addressing rank reversal issue that is the change in the ranking of the alternatives when a non-optimal alternative is introduced (Ertuğrul and Karakaşoğlu, 2008).
- With the integration of AHP and TOPSIS, the limitation of not checking the consistency ratio by TOPSIS is eliminated.

5.4. Solution Methodology

Based on the above discussion an integrated AHP and TOPSIS is applied for the selection of collection methods. In the classical AHP and TOPSIS methods, the weights of the criteria and the ratings of alternatives are known precisely and crisp values are used in the evaluation process. However, due to the complexity and uncertainty involved in real-world decision problems, decision makers may be reluctant to provide crisp judgments. Therefore, the fuzzy AHP and fuzzy TOPSIS method are proposed where ratings of alternatives are evaluated by linguistic variables represented by fuzzy numbers to deal with the deficiency of the traditional method. The fuzzy AHP is used to calculate the criteria weight and fuzzy TOPSIS is used to rank the alternatives. The various steps of the proposed methodology are shown in Figure 5.2 and critical steps are elucidated next.

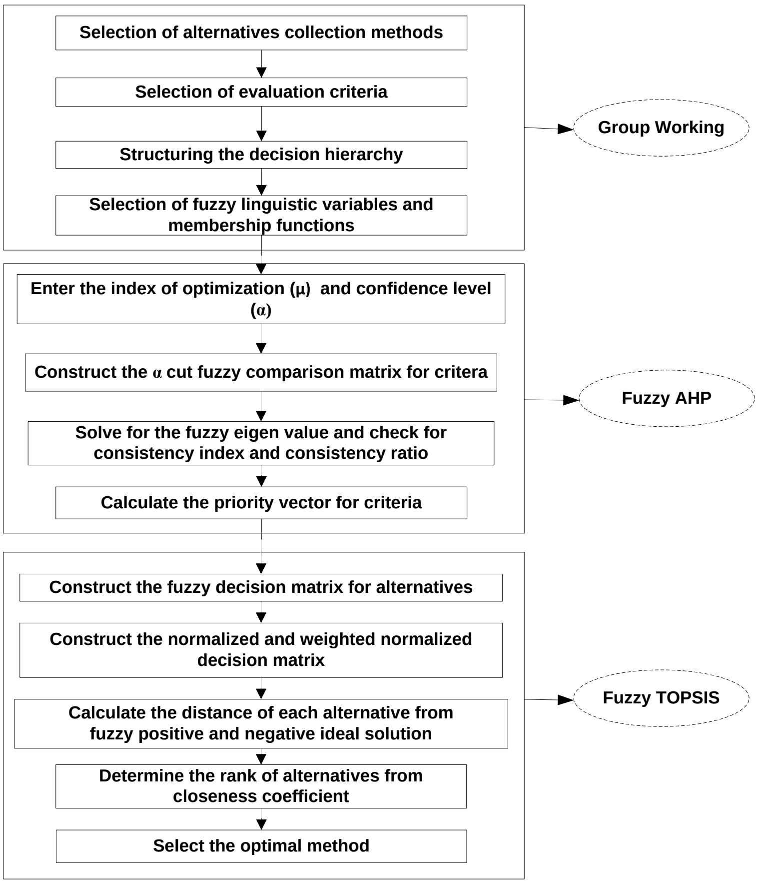

Figure 5.2 The proposed research methodology

5.4.1 Selection of alternative collection methods

The first step is to select the alternative collection methods from literature review and discussion with experts (i.e. managers working in supply chain management). Three selected alternatives for this study are: collection directly by original equipment manufacturer (A1), collection by retailers (A2) and collection by third party logistics providers (A3).

5.4.2 Selection of evaluation criteria

This step involves the selection of criteria for evaluating collection methods. These criteria are obtained from literature review and discussion held with experts. These criteria are divided into categories direct and indirect, where direct means more the better (i.e. value added recovery, return volume, degree of supply chain control, and level of customer satisfaction) and indirect means lesser the better (i.e. initial investment and operating cost).

The alternative collection methods and evaluation criteria are shown in Figure 5.1

5.4.3 Calculate criteria weight with fuzzy AHP

The essence of AHP is decomposition of a complex problem into a hierarchy (Figure 5.1) with goal at the top of the hierarchy, criterions, and sub-criterions at levels and sub-levels of the hierarchy, and decision alternatives at the bottom of the hierarchy (Pohekar and Ramachandran, 2004). After constructing a hierarchy the decision-maker(s) makes a pairwise comparison using triangular fuzzy numbers (Table 5.6) to estimate relative importance.

Table 5.6 Definition and membership function of fuzzy number

Intensity of Importance	**Fuzzy number**	**Definition**	**Membership function**
1	$\tilde{1}$	Equally important/preferred	(1,1,2)
3	$\tilde{3}$	Moderately more important/preferred	(2,3,4)
5	$\tilde{5}$	Strongly more important/preferred	(4,5,6)
7	$\tilde{7}$	Very strongly more important/preferred	(6,7,8)
9	$\tilde{9}$	Extremely more important/preferred	(8,9,10)

A triangular fuzzy number is denoted as $\tilde{M}$ = (l, m, u), where l ≤ m ≤ u, has the following triangular type membership function:

$$\mu_F(x) = \begin{cases} 0 & x < l \\ (x-l)/(m-l) & l \le x \le m \\ (u-x)/(u-m) & m \le x \le u \\ 0 & x > u \end{cases} \tag{5.1}$$

The fuzzy AHP procedure as given by Ayağ and Özdemir (2006) is followed here.

***Constructing the fuzzy comparison matrix**:* The fuzzy comparison matrix $\tilde{A}(a_{ij})$ is constructed using pairwise comparison and triangular fuzzy numbers as given by equation (5.2).

$$\tilde{A} = \begin{bmatrix} 1 & \tilde{a}_{12} & . & . & \tilde{a}_{1n} \\ \tilde{a}_{21} & & & & \\ . & & & & \\ . & & & & \\ \tilde{a}_{n1} & \tilde{a}_{n2} & & & 1 \end{bmatrix} \tag{5.2}$$

Where, $\tilde{a}_{ij} = 1$ if i = j (5.3)

$\tilde{a}_{ij} = \tilde{1}, \tilde{3}, \tilde{5}, \tilde{7}, \tilde{9}$ or $\tilde{1}^{-1}, \tilde{3}^{-1}, \tilde{5}^{-1}, \tilde{7}^{-1}, \tilde{9}^{-1}$, if $i \neq j$ (5.4)

***Solving for fuzzy eigenvalue**:* A fuzzy eigenvalue, $\tilde{\lambda}$ is a fuzzy number solution to

$$\tilde{A}\tilde{x} = \tilde{\lambda}\tilde{x} \tag{5.5}$$

To perform fuzzy multiplications and additions by using the interval arithmetic and α-cut, the equation $\tilde{A}\tilde{x} = \tilde{\lambda}\tilde{x}$ is equivalent to

$$[a_{i1l}^{\alpha} x_{1l}^{\alpha}, a_{i1u}^{\alpha} x_{1u}^{\alpha}] \oplus \ldots\ldots \oplus [a_{inl}^{\alpha} x_{nl}^{\alpha}, a_{inu}^{\alpha} x_{nu}^{\alpha}] = [\lambda x_{il}^{\alpha}, \lambda x_{iu}^{\alpha}] \tag{5.6}$$

where

$$\tilde{A} = [\tilde{a}_{ij}], \quad \tilde{x}^{t} = (\tilde{x}_1, \tilde{x}_2 \ldots\ldots \tilde{x}_n)$$

$$\tilde{a}_{ij}^{\alpha} = [\tilde{a}_{ijl}^{\alpha}, \tilde{a}_{iju}^{\alpha}], \quad \tilde{x}_i^{\alpha} = [\tilde{x}_{il}^{\alpha}, \tilde{x}_{iu}^{\alpha}], \quad \tilde{x}_i^{\alpha} = [\tilde{x}_{il}^{\alpha}, \tilde{x}_{iu}^{\alpha}]$$

For 0 ≤ α ≤ 1 and all i, j where i = 1, 2. . . n, j = 1, 2, . . n.

Therefore, the lower and upper limit of the fuzzy numbers with respect to α is as:

$$\begin{aligned} &\tilde{1}_{\alpha} = [1, 3 - 2\alpha] \\ &\tilde{3}_{\alpha} = [1 + 2\alpha, 5 - 2\alpha], \quad \tilde{3}_{\alpha}^{-1} = \left[\frac{1}{5 - 2\alpha}, \frac{1}{1 + 2\alpha}\right] \\ &\tilde{5}_{\alpha} = [3 + 2\alpha, 7 - 2\alpha], \quad \tilde{5}_{\alpha}^{-1} = \left[\frac{1}{7 - 2\alpha}, \frac{1}{3 + 2\alpha}\right] \\ &\tilde{7}_{\alpha} = [5 + 2\alpha, 9 - 2\alpha], \quad \tilde{7}_{\alpha}^{-1} = \left[\frac{1}{9 - 2\alpha}, \frac{1}{5 + 2\alpha}\right] \\ &\tilde{9}_{\alpha} = [7 + 2\alpha, 11 - 2\alpha], \quad \tilde{9}_{\alpha}^{-1} = \left[\frac{1}{11 - 2\alpha}, \frac{1}{7 + 2\alpha}\right] \end{aligned} \tag{5.7}$$

The α-cut is known to incorporate the decision maker(s) confidence over his/her preference or the judgment. The index of optimism (μ) is used to estimate the degree of satisfaction for the judgment matrix ($\tilde{A}$). The larger value of index μ indicates the higher degree of optimism. The index of optimism is a linear convex combination as defined by (Lee, 1995).

$$\tilde{a}_{ij}^{\alpha} = \mu \tilde{a}_{iju}^{\alpha} + (1-\mu)\tilde{a}_{ijl}^{\alpha}, \ \forall \mu \in [0,1] \tag{5.8}$$

While α is fixed, the following matrix can be obtained after setting the index of optimism (μ) in order to estimate the degree of satisfaction.

$$\tilde{A} = \begin{bmatrix} 1 & \tilde{a}_{12}^{\alpha} & . & . & \tilde{a}_{1n}^{\alpha} \\ \tilde{a}_{21}^{\alpha} & & & & \\ . & & & & \\ . & & & & \\ \tilde{a}_{n1}^{\alpha} & \tilde{a}_{n2}^{\alpha} & & & 1 \end{bmatrix} \tag{5.9}$$

The eigenvector is calculated by fixing the μ value and identifying the maximal eigenvalue. It will yield an interval set of values from a fuzzy number. Normalization of paired comparisons matrix and calculation of priority weights (approximate attribute weights) are also done before calculating $\lambda_{\max}$.

Calculating the consistency ratio and consistency index: The consistency ratio (CR) is used to estimate the consistency of pairwise comparisons. The CR is computed by dividing the Consistency Index (CI) by Random Index (RI). If the CR less than 0.10, the comparisons are acceptable, otherwise rejected. RI is the average index for randomly generated weights (Saaty, 1980).

$$CI = \frac{\lambda_{\max} - n}{n-1}, \quad CR = \frac{CI}{RI} \tag{5.10}$$

5.4.4 Assessment of alternative collection methods with fuzzy TOPSIS

This section presents the assessment of collection methods for reverse logistics using fuzzy TOPSIS.

Constructing the fuzzy decision matrix: First, each decision maker gives linguistic rating for all the alternatives with respect to each criterion, which are converted into triangular fuzzy number using Table 5.7

Table 5.7 Linguistic terms and fuzzy ratings for the alternatives

Linguistic Term	**Triangular Fuzzy Scale (*l*,*m*,*n*)**
Very Low (VL)	(1,1,3)
Low (L)	(1,3,5)
Medium (M)	(3,5,7)
High (H)	(5,7,9)
Very High (VH)	(7,9,9)

If the number of decision makers is ‘K’, then the aggregate fuzzy rating of all the decision makers is calculated using equation 5.11.

$$a_{ij} = \min_k \{a_{ijk}\},\ b_{ij} = 1/K \times \sum_{k=1}^{K} \{b_{ijk}\},\ c_{ij} = \max_k \{c_{ijk}\} \tag{5.11}$$

This aggregate assessment is used to convert the fuzzy decision matrix as shown below:

$$\tilde{D} = \begin{bmatrix} \tilde{a}_{11} & \tilde{a}_{12} & . & . & \tilde{a}_{1m} \\ \tilde{a}_{21} & & & & \\ . & & & & \\ . & & & & \\ \tilde{a}_{n1} & \tilde{a}_{n2} & & & \tilde{a}_{nm} \end{bmatrix} \tag{5.12}$$

Calculating the normalized and weighted normalized matrix: After getting the fuzzy decision matrix the next step is to normalize fuzzy decision matrix as:

$$\tilde{R} = [\tilde{r}_{ij}]_{m \times n},\ \text{i} = 1, 2. . . \text{m};\ \ \text{j} = 1, 2, . . . , \text{n} \tag{5.13}$$

where

$$\tilde{r}_{ij} = \left(\frac{a_{ij}}{c_j^*},\ \frac{b_{ij}}{c_j^*},\ \frac{c_{ij}}{c_j^*} \right) \text{ and } c_j^* = \max_i \{c_{ij}\} \ldots \text{(Direct Criteria)}$$

$$\tilde{r}_{ij} = \left(\frac{a_j^-}{c_{ij}},\ \frac{a_j^-}{b_{ij}},\ \frac{a_j^-}{a_{ij}} \right) \text{ and } a_j^- = \min_i \{a_{ij}\} \ldots \text{(Indirect Criteria)}$$

Then the weighted normalized matrix ($\tilde{V}$) is computed by multiplying the normalized fuzzy decision matrix $\tilde{r}_{ij}$ by the weights $\tilde{w}_j$ of evaluation criteria. The weights of criteria have been calculated with fuzzy AHP in section 5.4.3.

$$\tilde{V} = \left[\tilde{v}_{ij}\right]_{m\times n}, i = 1,2........m; j = 1,2......n \qquad (5.14)$$

where $\tilde{v}_{ij} = \tilde{r}_{ij}(\cdot)\tilde{w}_j$

Calculating the distance from fuzzy positive ideal solution (FPIS) and fuzzy negative ideal solution (FNIS): The distance of each weighted alternative ($\tilde{v}_{ij}$) from FPIS ($\tilde{v}_j^*$) and FNIS ($\tilde{v}_j^-$) is given by

$$d_i^* = \sum_{j=1}^{n} d_v(\tilde{v}_{ij,}\tilde{v}_j^*), \quad \forall i = 1,2......m \qquad (5.15)$$

$$d_i^- = \sum_{j=1}^{n} d_v(\tilde{v}_{ij,}\tilde{v}_j^-), \quad \forall i = 1,2......m \qquad (5.16)$$

where $d_v(\tilde{v}_{ij,}\tilde{v}_j^*)$ and $d_v(\tilde{v}_{ij,}\tilde{v}_j^-)$ are the distance measurements of $\tilde{v}_j^*$ and $\tilde{v}_j^-$ from $\tilde{v}_{ij}$, and are calculated by vertex method, i.e. if $\tilde{a} = (a_1, a_2, a_3)$, and $\tilde{b} = (b_1, b_2, b_3)$ are two triangular fuzzy numbers, then the vertex distance is given by:

$$d(a,b) = \sqrt{\frac{[(a_1 - b_1)^2 + (a_2 - b_2)^2 + (a_3 - b_3)^2]}{3}}$$

The FPIS and FNIS are defines as:

$$A^* = (\tilde{v}_1^* \quad \tilde{v}_2^* \quad .... \quad .... \quad \tilde{v}_n^*), \text{ where } \tilde{v}_j^* = \max{}_i \{v_{ij}\}, i = 1,2,......m; j = 1,2......n \qquad (5.17)$$

$$A^- = (\tilde{v}_1^- \quad \tilde{v}_2^- \quad .... \quad .... \quad \tilde{v}_n^-), \text{ where } \tilde{v}_j^- = \min{}_i \{v_{ij}\}, i = 1,2,......m; j = 1,2......n \qquad 5.18)$$

Ranking the alternatives using closeness coefficient: After calculating the distance, the next step is to calculate the closeness coefficient (CC_i). Closeness coefficient represents the distance of the alternative from the FNIS as a fraction of the total distance from FPIS and FNIS.

$$CC_i = d_i^- / (d_i^- + d_i^*), \quad \forall i = 1,2.......m \tag{5.19}$$

The alternatives are ranked according to the closeness coefficient (CC*i*) in decreasing order and the alternative with the highest closeness coefficient is selected for final implementation.

5.5. An Illustrative Example

In this section, an example is illustrated to prove the applicability and validity of the proposed decision making model. An automobile company is considered which wants to collect the end-of-use products from the customers. The returned products are low in volume and variety, but have a high value added recovery. The company is interested in high level of customer service and high degree of supply chain control. The alternative collection methods and the evaluation criteria are shown in Figure 5.1. First, the fuzzy comparison matrix of criteria (Table 5.8) is generated by practitioners working in the area of Indian automotive supply chain management using triangular fuzzy numbers. Using equation (5.7), α-cut fuzzy comparison matrix is generated with α = 0.5 and μ = 0.5 (Table 5.9). The fuzzy interval values in Table 5.9 are converted to crisp number using equation (5.8), which is further used to calculate the eigen values. Priority vector in Table 5.10 represents the importance weight of different criteria. The consistency ratio is also checked using equation (5.10) and is within limits (CR<0.01).

Table 5.8: Fuzzy comparison matrix of the criteria

	C1	**C2**	**C3**	**C4**	**C5**	**C6**
C1	1	$\tilde{7}^{-1}$	$\tilde{1}$	$\tilde{1}^{-1}$	$\tilde{5}^{-1}$	$\tilde{3}^{-1}$
C2	$\tilde{7}$	1	$\tilde{9}$	$\tilde{5}$	$\tilde{1}$	$\tilde{3}$
C3	$\tilde{1}^{-1}$	$\tilde{9}^{-1}$	1	$\tilde{3}^{-1}$	$\tilde{7}^{-1}$	$\tilde{5}^{-1}$
C4	$\tilde{1}$	$\tilde{5}^{-1}$	$\tilde{3}$	1	$\tilde{3}^{-1}$	$\tilde{1}^{-1}$
C5	$\tilde{5}$	$\tilde{1}^{-1}$	$\tilde{7}$	$\tilde{3}$	1	$\tilde{1}$
C6	$\tilde{3}$	$\tilde{3}^{-1}$	$\tilde{5}$	$\tilde{1}$	$\tilde{1}^{-1}$	1

Table 5.9: α-cut fuzzy comparison matrix for the criteria (α= 0.5, μ=0.5)

	C1	**C2**	**C3**	**C4**	**C5**	**C6**
C1	1	[1/8,1/6]	[1,2]	[1/2,1]	[1/6,1/4]	[1/4,1/2]
C2	[6,8]	1	[8,10]	[4,6]	[1,2]	[2,4]
C3	[1/2,1]	[1/10,1/8]	1	[1/4,1/2]	[1/8,1/6]	[1/6,1/4]
C4	[1,2]	[1/6,1/4]	[2,4]	1	[1/4,1/2]	[1/2,1]
C5	[4,6]	[1/2,1]	[6,8]	[2,4]	1	[1/2,1]
C6	[2,4]	[1/4,1/2]	[4,6]	[1,2]	[1/2,1]	1

Table 5.10: Eigen value for comparison of evaluation criteria

	C1	**C2**	**C3**	**C4**	**C5**	**C6**	**Priority Vector**
C1	1	0.1425	1.5	0.75	0.205	0.375	0.056
C2	7	1	9	5	1.5	3	0.393
C3	0.75	0.1125	1	0.375	0.1425	0.205	0.037
C4	1.5	0.205	3	1	0.375	0.75	0.094
C5	5	0.75	7	3	1	1.5	0.260
C6	3	0.375	5	1.5	0.75	1	0.160
λ_{max} = 6.235 CI= 0.0470, CR= 0.037<0.10							

After calculating the criteria weight, the ranking of alternative collection methods is done using fuzzy TOPSIS. First, a fuzzy decision matrix for alternatives (Table 5.11) is created in linguistic terms with the help of practitioners working in the area of Indian automotive supply chain management, which is further converted into triangular fuzzy number with the help of Table 5.17. It is further normalized using equation (5.13) and the normalized matrix is shown in Table 5.12. The normalized matrix is now converted into weighted normalized decision matrix (Table 5.13) using equation (5.14). This is used to calculate the distance of each alternative from FPIS and FNIS (Table 5.14) using equations (5.15) and (5. 16). Closeness coefficient is calculated using equation (5.19), and is shown in Table 5.15. The final ranking of alternatives is in the decreasing order of closeness coefficient and is shown in last row of Table 5.15.

Table 5.11: Fuzzy decision matrix for the alternatives

Criteria	**Alternatives**	**Decision Makers**			**Aggregate Fuzzy Rating**
		D1	**D2**	**D3**	
Initial Investment	A1	H	H	H	(5,7,9)
	A2	L	L	VL	(1,2.33,5)
	A3	M	VL	L	(1,3,7)
Value added recovery	A1	VH	VH	H	(5,8.33,9)
	A2	H	H	M	(3,6.33,9)
	A3	M	M	M	(3,5,7)
Return volume	A1	H	M	M	(3,5.67,9)
	A2	M	L	M	(1,4.33,7)
	A3	VH	H	VH	(5,8.33,9)
Operating cost	A1	H	H	VH	(5,7.67,9)
	A2	L	L	M	(1,3.67,7)
	A3	M	M	L	(1,4.33,7)
Degree of supply chain control	A1	VH	H	VH	(5,8.33,9)
	A2	H	M	H	(3,6.33,9)
	A3	M	L	M	(1,4.33,7)
Level of customer satisfaction	A1	VH	VH	VH	(7,9,9)
	A2	H	H	H	(5,7,9)
	A3	M	M	H	(3,5.67,9)

Table 5.12: Normalized fuzzy ratings for the alternatives

	A1	**A2**	**A3**	a_j^-	c_j^*
C1	(0.11,0.14,0.20)	(0.2,0.43,1)	(0.14,0.33,1)	1	9
C2	(0.56,0.93,1)	(0.33,0.7,1)	(0.33,0.56,0.78)	3	9
C3	(0.33,0.63,1)	(0.11,0.48,0.78)	(0.56,0.93,1)	1	9
C4	(0.11,0.13,0.2)	(0.14,0.27,1)	(0.14,0.23,1)	1	9
C5	(0.56,0.93,1)	(0.33,0.7,1)	(0.11,0.48,0.78)	1	9
C6	(0.78,1,1)	(0.56,0.78,1)	(0.33,0.48,1)	3	9

Table 5.13: Weighted normalized alternatives

	A1	A2	A3	FPIS	FNIS
C1	(0.01,0.01,0.01)	(0.01,0.02,0.06)	(0.01,0.02,0.06)	0.06	0.01
C2	(0.22,0.36,0.39)	(0.13,0.28,0.39)	(0.13,0.22,0.31)	0.39	0.13
C3	(0.01,0.02,0.04)	(0.00,0.02,0.03)	(0.02,0.03,0.04)	0.04	0.00
C4	(0.01,0.01,0.02)	(0.01,0.03,0.09)	(0.01,0.02,0.09)	0.09	0.01
C5	(0.14,0.24,0.26)	(0.09,0.18,0.26)	(0.03,0.12,0.20)	0.26	0.03
C6	(0.12,0.16,0.16)	(0.09,0.12,0.16)	(0.05,0.10,0.16)	0.16	0.05

Table 5.14: Distance of alternatives

	d_v(A1,A*)	d_v(A2,A*)	d_v(A3,A*)	d_v(A1,A-)	d_v(A2,A-)	d_v(A3,A-)
C1	0.05	0.03	0.04	0.00	0.03	0.03
C2	0.10	0.17	0.19	0.21	0.17	0.11
C3	0.02	0.02	0.01	0.02	0.02	0.03
C4	0.08	0.06	0.06	0.00	0.05	0.05
C5	0.07	0.11	0.16	0.19	0.16	0.11
C6	0.02	0.05	0.07	0.10	0.08	0.07

Table 5.15 Closeness coefficient for alternative collection methods

	A1	A2	A3
d_i^*	0.33	0.44	0.52
d_i^-	0.53	0.51	0.40
CC_i	0.61	0.54	0.43
Ranking of Collection Methods	1st	2nd	3rd

5.6. Results and Discussion

In this chapter an attempt has been made to use fuzzy logic with multi-criteria decision models for the assessment of collection methods in reverse logistics. The illustrative example shows that the proposed methodology is able to solve the multi-criteria decision problem for choosing the best collection alternative. The results show that value added recovery has highest weight (0.393) followed by degree of supply chain control (0.26) and customer satisfaction (0.16) as shown in Figure 5.3.

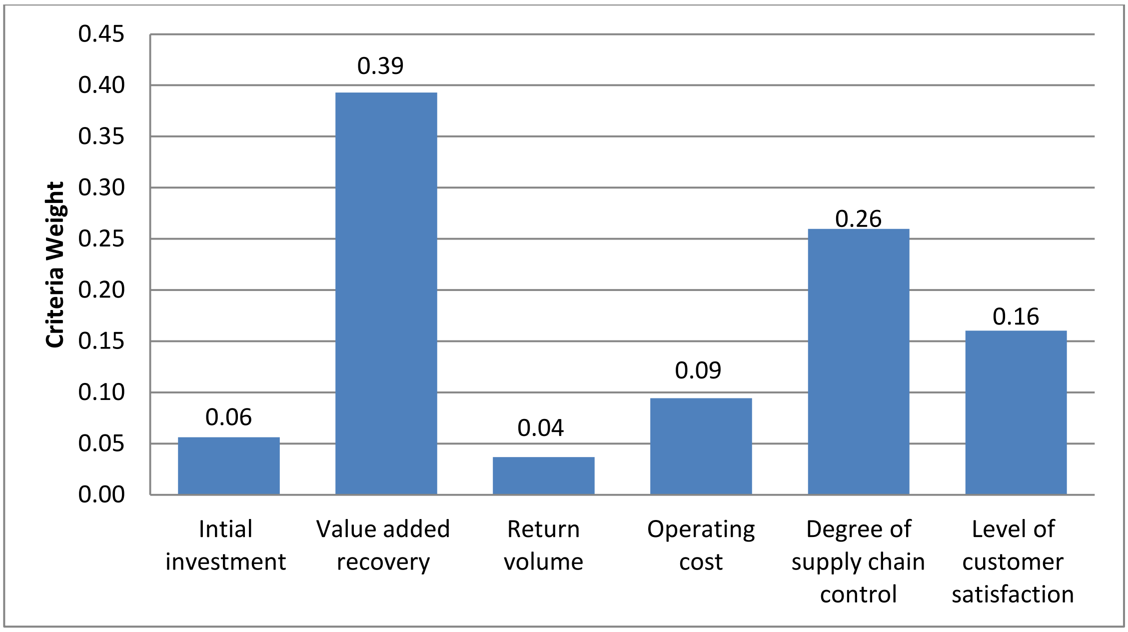

Figure 5.3 Weights for evaluation criteria

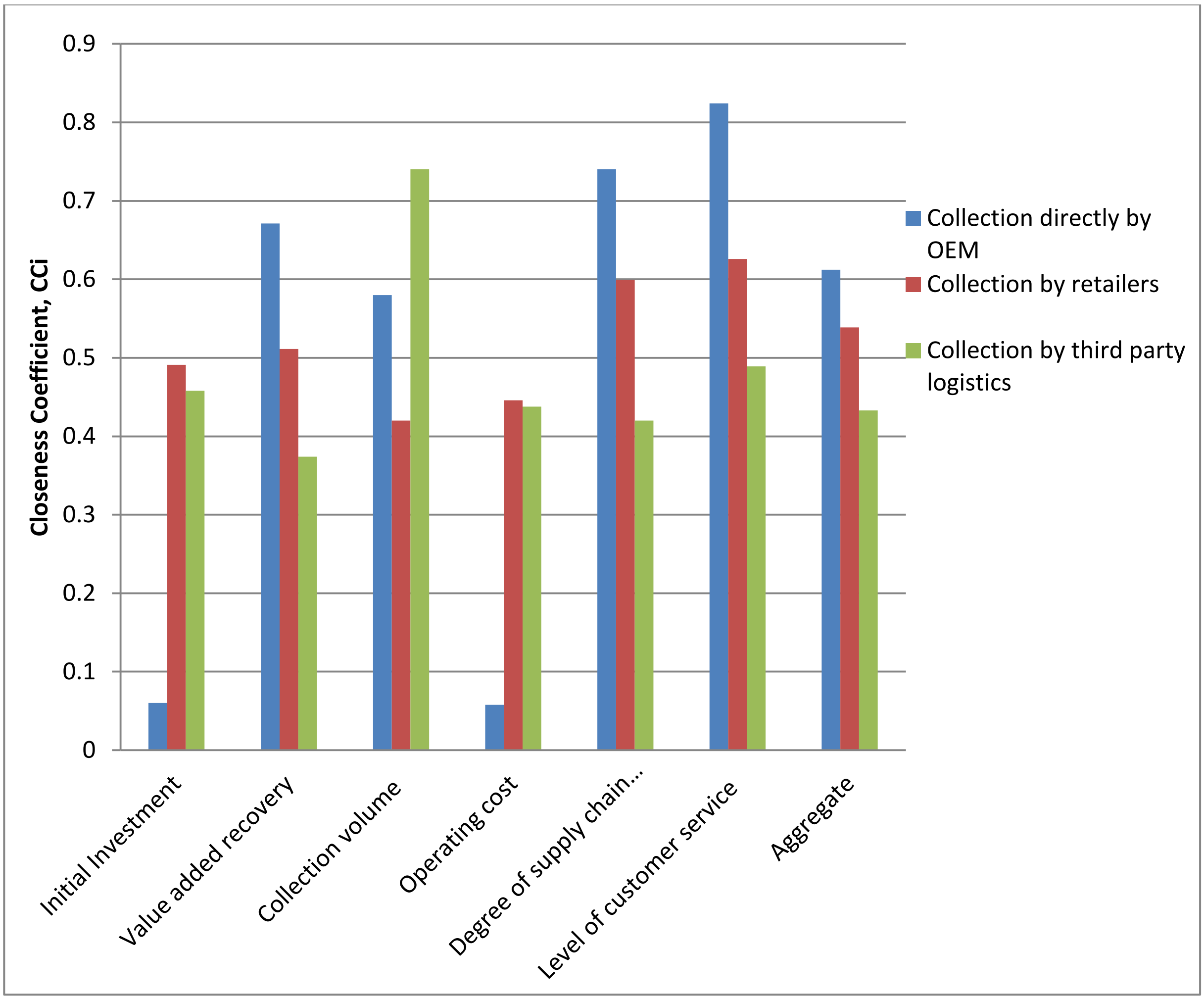

Figure 5.4 Ranking of alternative collection methods with respect to each and aggregate criteria

It demonstrates that the auto manufacturers are giving more weightage to the value added recovery and supply chain control as manufacturers do not want their propriety parts to reach grey market. It is believed that grey market remanufacturing may not provide 100% reliability and manufacturers are willing to share extra cost (both initial investment and operating cost) for customer satisfaction. That is why the weights for operating cost (0.094) and initial investment (0.056) criteria are low. The lowest weightage is given to the return volume criterion (0.037).

The ranking of alternative collection methods with respect to each and aggregate criteria is shown in Figure 5.4. With respect to initial investment; collection by retailers is the best methods followed by collection by third party logistics providers and collection directly by OEM is least preferred. With respect to the value added recovery collection directly by OEM is the best followed by collection by retailer and third party collection. With respect to degree of supply chain control and level of customers service the collection directly by OEM is the best method followed by collection by retailers and third party collection. Under the given circumstances, taking all the six criteria together the collection directly by the manufacturer is the best alternative and collection by third party logistics provider is the least preferred alternative.

CHAPTER 6

ASSESSMENT AND EVALUATION OF PRODUCT RECOVERY PROCESSES IN REVERSE LOGISTICS

This chapter aims at providing a multi-criteria decision model for the assessment and evaluation of alternate product recovery processes in reverse logistics. The assessment has been performed based on the criteria of operating cost, value added recovery, environmental impact, market demand, technical/operational feasibility, and corporate social responsibility. The five alternative product recovery processes identified in the study are repair, refurbishing, remanufacturing, cannibalizing, and recycling. The utility of the proposed methodology is validated through a case example from Indian electronic sector.

6.1. Introduction

Product recovery is another major element of reverse logistics. Product recovery management incorporates a supply chain that has been redesigned to manage the flow of products or parts destined for remanufacturing, repairing, or disposal and to effectively use the resources (Dowlatshahi, 2000). Owing to the revolution in green manufacturing for the global market; product recovery management concept plays a pivotal role in a company's competitive advantage and helps strategic decision making (Gungor and Gupta, 1999; Sasikumar and Kannan, 2008). It is an environmentally and economically sound way to achieve many of the goals of sustainable development (Ayres *et al.*, 1997; Ferrer, 1997a; Ferrer, 1997b; Thierry *et al.*, 1995). Kim *et al.*(2008) in their case study of automotive alternators, found that a remanufactured alternator uses 20% lesser materials, 16% lesser energy and releases only 35% of the greenhouse gases when compared with the process of producing a new product. Product recovery management includes strategies to increase product life consisting of repairing, remanufacturing and finally recycling products (Guide Jr and Srivastava, 1997). Therefore, developing a comprehensive and cost-effective decision system for product recovery is a daunting challenge that reaches well beyond the operational level for decision makers.

Assessment of product recovery processes has always been a challenge due to its interdisciplinary and multi-criteria complexity. Specially, when there are a number of reprocessing alternatives like repair, refurbish, remanufacture, cannibalize or recycle (Thierry *et al.*, 1995). The assessment of product recovery processes is affected by multiple criteria like operating cost, value added recovery, legislation, technical feasibility, market demand, and environmental impact. The presence of multiple criteria and the involvement of multiple decision-makers increase the complexity of product recovery process assessment. It is further complicated because of high level of uncertainty in quantity, quality and time of product return. So, a flexible decision making system is required to choose the alternative process based on input given by the experts.

In this chapter, an integrated fuzzy analytic hierarchy process (Fuzzy AHP) and fuzzy technique for order preference by similarity to ideal situation (Fuzzy TOPSIS) is used for the product recovery process assessment and evaluation. With the integration of AHP and TOPSIS, the proposed methodology will have the advantages of both as discussed in section 5.3.3. AHP is used to calculate the criteria weight and TOPSIS is used to find the ranking of alternative product recovery processes using linguistic variables. However, due to the vagueness and uncertainty on judgments of the decision-maker(s), the crisp pairwise comparison in the conventional AHP and TOPSIS seems to be insufficient and imprecise to capture the right judgments of decision-maker(s). Therefore, fuzzy mathematics is introduced to make up for this deficiency in the conventional methodology to evaluate the different product recovery processes. These decisions regarding the assessment of reprocessing alternatives can help companies to prioritize and develop reverse manufacturing facilities accordingly.

6.2. Model Development

With the increasing attention to global environment and resource problems, traditional supply chain has been expanded to closed-loop supply chain using different product recovery processes to recover the added value or material. Different product recovery processes as discussed in literature can be repair, refurbishing, remanufacturing, cannibalization, and recycle. Further the assessment and evaluation of product recovery processes is affected by multiple criteria like operating cost, value added recovery, legislation, technical feasibility, market demand, and environmental impact. The following text provides a discussion on theses product recovery processes and the criteria for their assessment and evaluation.

6.2.1 Alternative product recovery processes

As discussed in literature review (chapter 2) section 2.3.3 (Table 2.4) different authors categorize and classify the product recovery processes differently. The five product recovery alternatives selected are: repair, refurbishing, remanufacturing, cannibalization, and recycle. Destroying (landfill or incineration) is not considered as product recovery process as this is a part of waste disposal techniques. Similarly, direct reuse or repackaging are not considered in product recovery processes as they require only minimal or superficial processing (Parkinson and Thompson, 2003; Thierry *et al.*, 1995). The following discussion on these product recovery processes is based on, but not limited to, the works of Toensmeier (1992), Thierry *et al.* (1995), King *et al.*(2006), Parkinson and Thompson (2003) and McConocha and Speh (1991).

(i) Repair

Repair is the most logical approach to close the product recovery cycle to extend the product life. However, this is intrinsically a simple concept, its practice is low and little research has been undertaken to understand this closed-loop option (King *et al.*, 2006). The purpose of repair is to return the used products to working order. Product repair involves fixing and/or replacement of broken parts. The other parts are basically not affected. Repair of a few parts may return equipment to an operational state. It requires limited product disassembly. It may cost 40% to 50% for a small machine and covered by a short warranty. The quality of the repaired products could be lower than that of the new products (Ayres *et al.*, 1997; King *et al.*, 2006). Warranty of repaired product is generally less than those of newly manufactured equivalents. The warranty may not cover the whole product but only the replaced component (King *et al.*, 2006).

(ii) Refurbishing

Refurbishing involves less work content than remanufacturing, but more than that of repairing. Refurbishing is to bring the quality of used products up to a specified or reusable level by disassembly, inspection and replacement of broken modules. Quality standards in refurbishing are less rigorous than those for new products. In refurbishing, degree of disassembly is up to module level where all the critical modules are inspected and fixed or replaced. Refurbishing could also involve technology up-gradation by replacing outdated modules with technologically superior ones. It is often practiced in computer hardware industry for technical up-gradation and in public transportation industry to maintain a new appearance of the equipment or for safety reasons.

(iii) Remanufacturing

In remanufacturing, the entire equipment is disassembled at the module and part level to repair or substitute parts and modules that are worn out or obsolete. Parts subject to wear or clogging are replaced. It is to bring the used products up to quality standards that are as rigorous as those for new products by complete disassembly down to the component level, and extensive inspection and replacement of broken/outdated parts. Remanufacturing involves the greatest degree of work content and as a result remanufactured products have superior quality and reliability. Thierry *et al.* (1995) reported that remanufactured products have the same quality as a new product and are sold with the same warranty. It recovers most of the labour, material and energy value added during manufacturing. Remanufacturing has also been shown to be environmentally preferable in comparison with other end-of-life treatments, since the geometrical form of the product is retained and its associated economic and environmental values preserved (Kerr and Ryan, 2001).

(iv) Cannibalization

In the previous product recovery options, a large proportion of the retuned products are recovered. But in cannibalization a relatively small number of reusable parts and modules are recovered from the retuned products which are to be used in repair, refurbishing and remanufacturing of other products (Thierry *et al.*, 1995). Quality standards of cannibalized parts depend on the process in which they will be used. Cannibalization involves selective disassembly and inspection of reusable parts. The remaining parts or modules are not used in cannibalization.

(v) Recycling

The goal of repair, refurbishing and remanufacturing is to retain the identity and functionality of used product or parts as much as possible. In recycling the identity and functionally of the recovered product or part is lost. The goal of recycling is to recover the material without concerning the conservation of product structures. Recycling serves to recover materials from used products by various separation processes and reuse them in the production of the original or other products. According to the Northeast Recycling Council (NERC), recycling activity in New York in 1997 reduced energy use by 9%, sulphur oxide emissions by 12% and saved 2.7 million tons of iron ore to be extracted to form new materials. Thus, it is environmentally better to recycle materials rather than to take them to a landfill site. Energy saving for aluminium can be as high as 91% by recycling scrap compared with the process of using the primary raw material, bauxite (King *et al.*, 2006).

6.2.2 Criteria for the assessment of product recovery processes

Assessment of product recovery processes is effected by various criteria. Stahel (1994) proposed that, in terms of profit and energy consumption, repair is the best recovery process followed by remanufacturing and recycling. King *et al.*(2006) explained it by second law of thermodynamics that entropy of a closed system always increases and each transforming process requires additional energy. The same is true in product recovery. The high-energy material comes at the start and gradually becomes more disordered to the final state of waste. Thus, recycling (using highly disordered material) requires more ‘corrective’ energy than remanufacturing (where the primary shape is preserved), which in turn requires more than reconditioning and repair. Repair also has the added societal benefits of providing employment to low and medium skilled labour because many of repair tasks are simple to learn.

Srivastava (2008), in his model for reverse logistics, discussed that repair/refurbish is more skill based and requires low capital investment, but remanufacturing requires high initial investment and is more technology based. Guide *et al.*(2000) also discussed that repair, remanufacture and recycle operations require varying amounts of effort to reuse materials and products. Zikopoulos and Tagaras (2007) investigated the impact of uncertainty in the quality of used product returns on the profitability of reuse activities.

Zhuolun (2008) proposed a conceptual framework to support product recovery decisions and presented that value from returned product decreases in the order of reuses, refurbish, remanufacture, cannibalize, recycle, and disposal of the products. Krikke *et al.* (1998) proposed a model for evaluating recovery strategies for the product without violating the physical and economical feasibility constraints. Wadhwa *et al.* (2009) considered cost, environmental impact, market factor, quality factor, and legislative factor as the criteria to develop a decision support tool based on fuzzy TOPSIS for product recovery selections. However, the value added recovery and corporate social responsibility are not considered as the evaluating criteria. From the literature review and discussion held with experts working in supply chain management, it is concluded that the selection of product recovery process depends on multiple criteria like operating cost, value added recovery, environmental impact, technical feasibility, market demand, and corporate social responsibility. A brief explanation of these evaluation criteria are given in Table 6.1. Figure 6.1 shows the proposed model for product recovery assessment.

Table 6.1 Evaluation criteria for assessment of product recovery processes

Evaluation Criteria	**Explanation**
Operating cost (C1)	Operating cost is a key factor of product recovery process selection and implementation (Lee *et al.*, 2001). Operating cost will be different for different product recovery processes as it depends on the degree of disassembly and desired quality level. Each recovery process has different degree of disassembly and quality level. For example, repair/refurbishing requires less disassembly as compared to remanufacturing.
Environmental impact (C2)	Environmental impact of product recovery process can be measured in terms of resource consumption, resource conservation and amount of waste generated. Different product recovery processes have different value of these parameters and therefore different environmental impact (Shih, 2001). From environmental impact point of view reuse is the best process and disposal is the worst one.
Market demand (C3)	Selection of product recovery process also depends on the market demand (Rose and Ishii, 1999). If there is a market demand for refurbished or remanufactured products then only the organization will select these as the recovery alternatives otherwise organizations may select recycling for material recovery. The choice of recovery process also depends on the quality standard desired in the market (Wadhwa *et al.*, 2009). Remanufacturing provides highest reliability and quality.

Table 6.1 Evaluation criteria for assessment of product recovery processes (contd.)

Evaluation Criteria	**Explanation**
Technical/operational feasibility (C4)	A very serious problem faced by the firms in the implementation of product recovery management is the lack of technical or operational feasibility (Ishii *et al.*, 2002). Different product recovery processes require different technical/operational feasibility to provide the required level of quality and disassembly. The selection of product recovery process depends on the technical/operational feasibility of the system. Remanufacturing is more technology based as compared to repair/refurbishing.
Corporate social responsibility (C5)	Product recovery is a labour-intensive industry and provides jobs to the lower-skilled labour (Parkinson and Thompson, 2003). Different product recovery processes provide different number of jobs and to differently qualified people. Studies have indicated that recycling activities create 5 to 7 times the number of jobs than incineration and more than 10 times than land filling operations (De Brito, 2004). Dehghanian and Mansour (2009) have also discussed that different recovery processes create different number of job opportunities.
Value added recovery (C6)	Product recovery provides cost benefit by value added recovery of the returned products. Different product recovery processes provide different value added recovery. Reuse recovers the maximum value followed by refurbish, remanufacture, cannibalize, recycle and disposal.

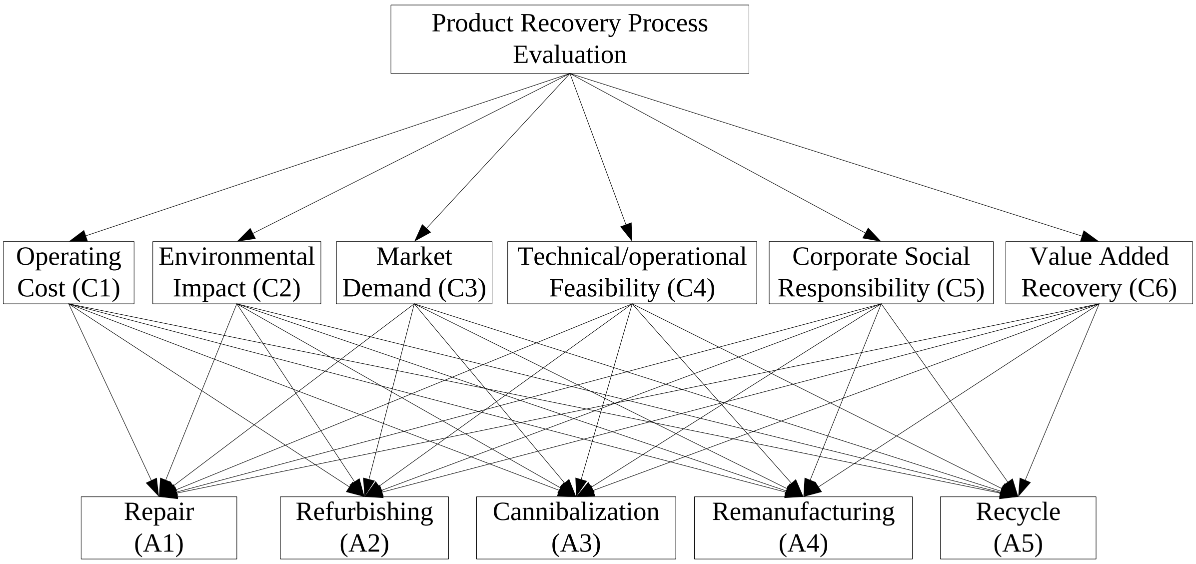

Figure 6.1 Hierarchy of product recovery process selection

6.3. Solution Methodology with Illustrative Example

An integrated fuzzy AHP and fuzzy TOPSIS multi-criteria model is proposed for the assessment of product recovery processes. Fuzzy AHP is used to calculate the criteria weight while fuzzy TOPSIS is used for the ranking of alternative product recovery processes. The detailed discussion on the advantages of integrated AHP and TOPSIS is provided in section 5.3.3. As a case example, product recovery management of an electronic product is taken into consideration. The detailed solution methodology has been provided in section 5.4 and is briefly given below with illustrative example.

6.3.1 Selection of alternative product recovery processes

The first step is to select the alternative product recovery processes from literature review and discussion with experts working in the area of product recovery or supply chain management. The selected alternative product recovery processes are repair (A1), refurbishing (A2), cannibalizing (A3), remanufacturing (A4), and recycle (A5) as shown in Figure 6.1.

6.3.2 Selection of evaluation criteria

This step involves the selection of criteria for evaluating alternative product recovery processes. These criteria are obtained from literature review and discussion held with experts working in the area of supply chain management. Six criteria selected for the present problem are given in Table 6.2 and also shown in Figure 6.1. These criteria are further divided into direct and indirect criteria where direct means more the better (e.g. market demand) and indirect means lesser the better (e.g. operating cost).

6.3.3 Calculate criteria weights with fuzzy AHP

The AHP method was first introduced by Saaty (1980) and is also known as an eigenvector method. It indicates that the eigenvector corresponding to the largest eigenvalue of the comparisons matrix provides the relative priorities of the factors. The methodology given by Ayağ and Özdemir (2006) is used to calculate the weight of criteria. The various steps to calculate the criteria weights are mentioned in detail in section 5.4.3. These steps are used here to elucidate the case example.

Table 6.2: Criteria influencing product recovery process

Criteria	Criteria Type
Operating cost (C1)	Indirect
Environmental impact (C2)	Indirect
Market demand (C3)	Direct
Technical/operational feasibility (C4)	Indirect
Corporate social responsibility (C5)	Direct
Value added recovery (C6)	Direct

***Constructing the fuzzy comparison matrix of criteria**:* The fuzzy comparison matrix for criteria is constructed by the input from experts of supply chain management. Table 6.3 shows the pairwise comparison of criteria using triangular fuzzy numbers.

Table 6.3 Fuzzy comparison matrix of the criteria

	C1	C2	C3	C4	C5	C6
C1	1	$\tilde{7}$	$\tilde{1}$	$\tilde{3}$	$\tilde{9}$	$\tilde{1}$
C2	$\tilde{7}^{-1}$	1	$\tilde{5}^{-1}$	$\tilde{3}^{-1}$	$\tilde{1}$	$\tilde{5}^{-1}$
C3	$\tilde{1}^{-1}$	$\tilde{5}$	1	$\tilde{1}$	$\tilde{7}$	$\tilde{1}^{-1}$
C4	$\tilde{3}^{-1}$	$\tilde{3}$	$\tilde{1}^{-1}$	1	$\tilde{5}$	$\tilde{3}^{-1}$
C5	$\tilde{9}^{-1}$	$\tilde{1}^{-1}$	$\tilde{7}^{-1}$	$\tilde{5}^{-1}$	1	$\tilde{7}^{-1}$
C6	$\tilde{1}^{-1}$	$\tilde{5}$	$\tilde{1}$	$\tilde{3}$	$\tilde{7}$	1

***Solving for fuzzy eigenvalue**:* The α-cut fuzzy comparison matrix is generated from the fuzzy comparison matrix after substituting $\alpha = 0.5$ in equation (5.7). The α-cut fuzzy comparison matrix is shown in Table 6.4. The fuzzy interval values in Table 6.4 are converted into crisp numbers by substituting $\mu = 0.5$ in equation (5.8), which is further used to calculate the eigen values as shown in Table 6.5.

Table 6.4: α- Cut fuzzy comparison matrix of the criteria

	C1	C2	C3	C4	C5	C6
C1	1	[6,8]	[1,2]	[2,4]	[8,10]	[1,2]
C2	[1/8,1/6]	1	[1/6,1/4]	[1/4,1/2]	[1,2]	[1/6,1/4]
C3	[1/2,1]	[4,6]	1	[1,2]	[6,8]	[1/2,1]
C4	[1/4,1/2]	[4,6]	[1/2,1]	1	[4,6]	[1/4,1/2]
C5	[1/10,1/8]	[1/2,1]	[1/8,1/6]	[1/6,1/4]	1	[1/8,1/6]
C6	[1/2,1]	[4,6]	[1,2]	[2,4]	[6,8]	1

Table 6.5: Eigen vector for comparison of criteria

	C1	C2	C3	C4	C5	C6	Priority Vector
C1	1	7	1.5	3	9	1.5	0.323
C2	0.1455	1	0.21	0.375	1.5	0.21	0.046
C3	0.75	5	1	1.5	7	0.75	0.208
C4	0.375	3	0.75	1	5	0.375	0.129
C5	0.115	0.75	0.15	0.21	1	0.15	0.032
C6	0.75	5	1.5	3	7	1	0.262
λ_{max} = 6.264, CI= 0.0528, RI= 1.25, CR= 0.042 < 0.10							

***Calculating the consistency ratio and consistency index**:* The eigen values are checked for consistency ratio (CR) using equation (5.10). The CR for this case is coming out to be 0.042, which is under the specified limit of 0.10. The criteria weight is represented by the priority vector in Table 6.5.

6.3.4 Assessment of alternative product recovery processes with fuzzy TOPSIS

The various steps to Fuzzy TOPSIS are mentioned in detail in section 5.4.4. These steps are used here to elucidate the case example.

***Constructing the fuzzy decision matrix of alternatives**:* After calculating the criteria weights, decision makers provide linguistic rating for all the alternatives with respect to each criterion, as shown in Table 6.6. This linguistic rating is converted into triangular fuzzy number using Table 5.7 to get fuzzy decision matrix (Table 6.7).

Table 6.6: Linguistic rating of alternatives with respect to each criterion

	A1	**A2**	**A3**	**A4**	**A5**
C1	VL	M	M	H	L
C2	VL	VL	M	L	H
C3	M	H	L	H	L
C4	L	H	M	VH	L
C5	H	M	M	VH	L
C6	VH	H	L	H	VL

Table 6.7: Fuzzy decision matrix for the alternatives

	A1	**A2**	**A3**	**A4**	**A5**	a_j^-	c_j^*
C1	(1,1,3)	(3,5,7)	(3,5,7)	(5,7,9)	(1,3,5)	1	9
C2	(1,1,3)	(1,1,3)	(3,5,7)	(1,3,5)	(5,7,9)	1	9
C3	(3,5,7)	(5,7,9)	(1,3,5)	(5,7,9)	(1,3,5)	1	9
C4	(1,3,5)	(5,7,9)	(3,5,7)	(7,9,9)	(1,3,5)	3	9
C5	(5,7,9)	(3,5,7)	(3,5,7)	(7,9,9)	(1,3,5)	1	9
C6	(7,9,9)	(5,7,9)	(1,3,5)	(5,7,9)	(1,1,3)	1	9

***Calculating the normalized and weighted normalized matrix**:* After getting the fuzzy decision matrix the next step is to normalize fuzzy decision matrix (Table 6.8) using equation (5.13). The normalized ratings are converted into weighted normalized rating (Table 6.9), by using equation (5.14) and weights of criteria shown in Table 6.5.

Table 6.8: Normalized fuzzy ratings for the alternatives

	A1	**A2**	**A3**	**A4**	**A5**
C1	(0.33,1,1)	(0.14,0.2,0.33)	(0.14,0.2,0.33)	(0.11,0.14,0.2)	(0.2,0.33,1)
C2	(0.33,1,1)	(0.33,1,1)	(0.11,0.14,0.2)	(0.2,0.33,1)	(0.11,0.14,0.2)
C3	(0.33,0.55.0.77)	(0.55,0.77,1)	(0.11,0.33,0.77)	(0.55,0.77,1)	(0.11,0.33,0.55)
C4	(0.2,0.11,0.33)	(0.11,0.14,0.2)	(0.14,0.2,0.33)	(0.11,0.11,0.14)	(0.2,0.33,1)
C5	(0.55,0.77,1)	(0.33,0.55,0.77)	(0.33,0.55,0.77)	(0.77,1,1)	(0.11,0.33,0.55)
C6	(0.77,1,1)	(0.55,0.77,1)	(0.11,0.33,0.55)	(0.55,0.77,1)	(0.11,0.33,0.55)

***Calculating the distance of alternatives from fuzzy positive ideal solution (FPIS) and fuzzy negative ideal solution (FNIS)**:* From Table 6.9, distance of each alternative from the FPIS and FNIS is calculated using equations (5.15) and (5.16). The calculated distance of each alternative from the FPIS and FNIS is shown in Table 6.10.

Table 6.9 Weighted normalized alternatives

	A1	**A2**	**A3**	**A4**	**A5**	**FPIS**	**FNIS**
C1	(0.107,0.322,0.322)	(0.046,0.064,0.107)	(0.046,0.064,0.107)	(0.035,0.046,0.064)	(0.064,0.107,0.322)	0.323	0.036
C2	(0.015,0.046,0.046)	(0.015,0.046,0.046)	(0.005,0.006,0.009)	(0.009,0.015,0.046)	(0.005,0.006,0.009)	0.046	0.005
C3	(0.069,0.115,0.161)	(0.115,0.161,0.207)	(0.023,0.069,0.161)	(0.115,0.161,0.207)	(0.023,0.069,0.115)	0.208	0.023
C4	(0.025,0.042,0.128)	(0.014,0.018,0.025)	(0.018,0.025,0.042)	(0.014,0.014,0.018)	(0.025,0.042,0.128)	0.129	0.014
C5	(0.017,0.025,0.032)	(0.010,0.017,0.025)	(0.010,0.017,0.025)	(0.025,0.032,0.032)	(0.003,0.010,0.017)	0.032	0.004
C6	(0.203,0.262,0.262)	(0.145,0.203,0.262)	(0.029,0.087,0.145)	(0.145,0.203,0.262)	(0.029,0.029,0.087)	0.262	0.029

Table 6.10 Distance of alternatives from FPIS and FNIS

	$d_v(A1,A^*)$	$d_v(A2,A^*)$	$d_v(A3,A^*)$	$d_v(A4,A^*)$	$d_v(A5,A^*)$	$d_v(A1,A^-)$	$d_v(A2,A^-)$	$d_v(A3,A^-)$	$d_v(A4,A^-)$	$d_v(A5,A^-)$
C1	0.124	0.251	0.251	0.274	0.194	0.238	0.045	0.045	0.018	0.171
C2	0.018	0.018	0.039	0.028	0.039	0.034	0.034	0.003	0.025	0.003
C3	0.100	0.060	0.136	0.060	0.144	0.100	0.144	0.084	0.144	0.060
C4	0.077	0.109	0.100	0.113	0.077	0.068	0.007	0.018	0.002	0.068
C5	0.009	0.016	0.016	0.004	0.022	0.022	0.016	0.016	0.027	0.009
C6	0.034	0.075	0.181	0.075	0.215	0.215	0.181	0.075	0.181	0.034

Ranking the alternatives using closeness coefficient: After calculating the distance, the next step is to calculate the closeness coefficient (CC_i) for each alternative using equation (5.19). The calculated values of closeness coefficient are shown in Table 6.11. Closeness coefficient represents the distance of the each alternative from the FNIS as a fraction of the total distance from FPIS and FNIS.

Table 6.11 Closeness coefficient for alternatives

	A1	A2	A3	A4	A5
d_i^*	0.362081	0.528773	0.723401	0.553934	0.69199
d_i^-	0.677797	0.426334	0.24055	0.39585	0.344998
CC_i	0.651804	0.446373	0.249546	0.416779	0.332693

Now the alternatives are ranked in the decreasing order of closeness coefficient as shown in Table 6.12. Higher the closeness coefficient means better the ranking. Therefore, in the case example repair is the best product recovery alternative followed by refurbishing, remanufacturing, recycling, and cannibalizing.

Table 6.12 Ranking of alternative product recovery processes

Alternative Product Recovery Processes	Ranking
Repair (A1)	1st
Refurbish (A2)	2nd
Remanufacture (A4)	3rd
Recycle (A5)	4th
Cannibalize (A5)	5th

6.4. Results and Discussion

This chapter presented a fuzzy multi-criteria decision model for the assessment and evaluation of alternative product recovery processes. The illustrative example of Indian electronic manufacturer shows that the proposed methodology is able to solve the multi-criteria decision problem for choosing the best product recovery alternative. The results show that operating cost has the highest weight (0.323) followed by value added recovery (0.262), market demand (0.208), technical/operational feasibility (0.129), environmental impact (0.046), and corporate social sustainability (0.032) as shown in Figure 6.2. This demonstrates that the electronic manufacturers in India are more oriented to save operating costs, recover maximum value and market demand rather than the environmental impact and corporate social sustainability.

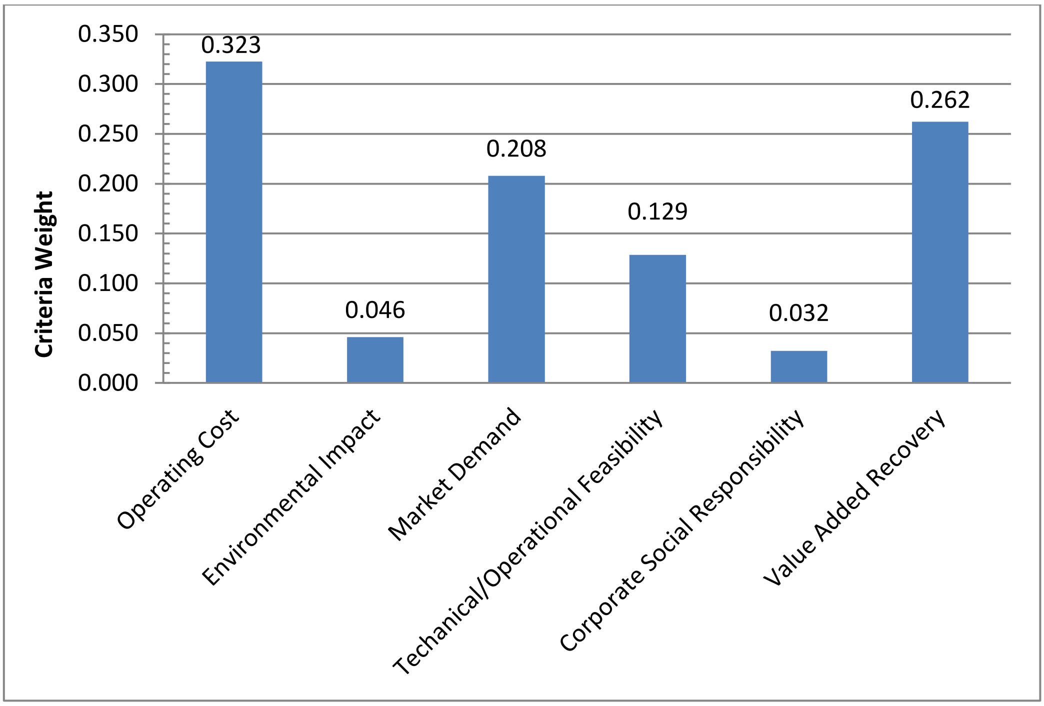

Figure 6.2 Weights for evaluating criteria

The final ranking of the alternative recovery processes in term of closeness coefficient for individual criterion and the aggregate are shown in Figure 6.3. Higher the values of closeness coefficient better the alternative. Therefore, with respect to operating cost repair is best recovery process followed by recycle. Remanufacturing is the least preferred alternative process with a very low value of closeness coefficient. This is because repair and recycle require least initial investment and degree of disassembly as compared to remanufacturing which requires high degree of disassembly and therefore high operating cost. In terms of environmental impact repair and refurbish are the best recovery alternatives closely followed by remanufacturing. Repair and refurbishing consume less resources and also generate less waste as compared to the other recovery alternatives. Recycle and cannibalization are the least preferred alternatives in terms of environmental impact as these processes require additional energy to convert the materials into useful products. With respect to market demand refurbished and remanufactured products are preferred as these processes provide the desired reliability and quality standards. Remanufacturing provides reliability as high as of new product if not more. However, remanufacturing requires each part to be disassembled, therefore a high degree of work content is involved. Therefore the technical/operational feasibility of the process is low. But because of high work content, the number of job opportunities increases in remanufacturing and therefore it is most preferred in terms of corporate social responsibility followed by repair. Further with respect to value added recovery repair is the best followed by refurbish and recycle is the least preferred. In recycling, all the value added during manufacturing is lost and only material value is recovered.

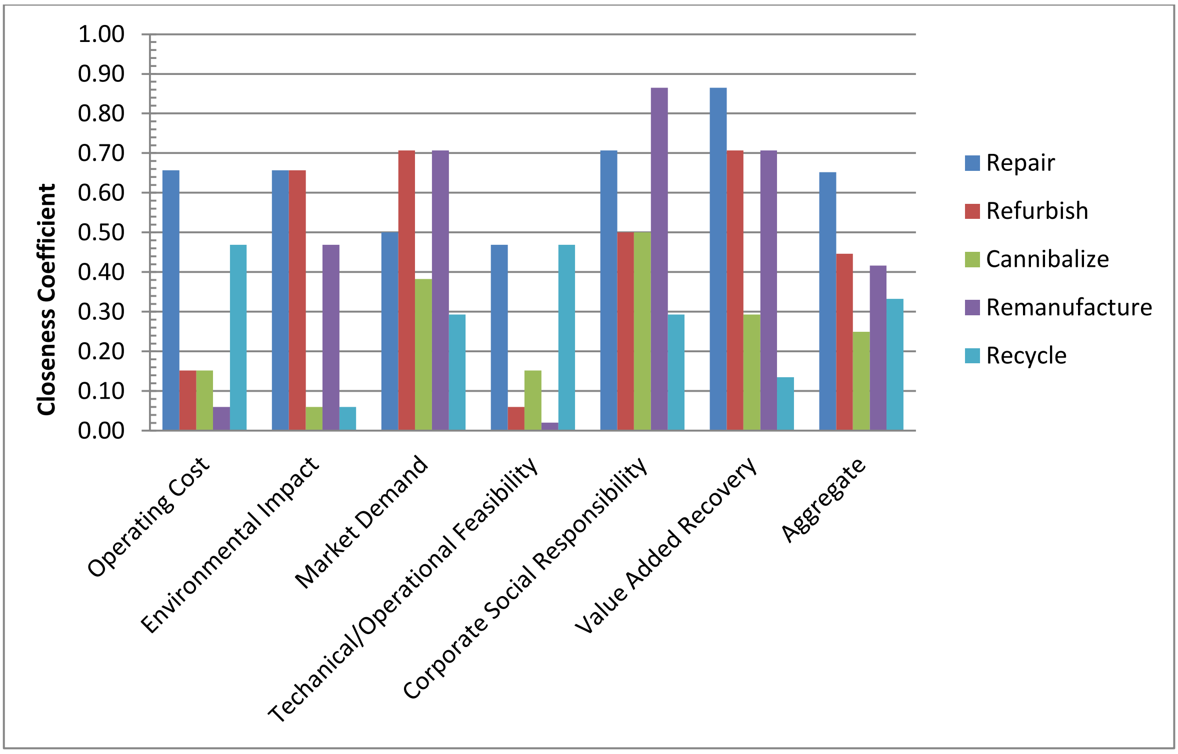

Figure 6.3 Closeness coefficient of product recovery alternatives and aggregate closeness coefficient

Repair is the best recovery process with respect to operating cost, environmental impact, technical/operational feasibility, and value added recovery. Remanufacturing is the best product recovery alternative with respect to market demand and corporate social sustainability. Overall (aggregate) repair is the best product recovery alternative followed by refurbishing, remanufacturing, recycling, and cannibalizing under the given circumstances.

CHAPTER 7

ASSESSMENT AND EVALUATION OF NETWORK CONFIGURATIONS IN REVERSE LOGISTICS

This chapter aims at providing a multi-criteria decision model for the assessment and evaluation of alternative network configurations in reverse logistics. Literature suggests eight different network configurations of reverse logistics based on the trade-offs at collection stage, sorting/testing stage and processing stage of products. These network configurations are evaluated based on the economical, environmental and social criteria. The utility of the proposed methodology has been validated by thorough a case example from Indian automotive sector.

7.1. Introduction

Sustainability, as defined by its 'triple-bottom line' factors of economic, environmental, and social dimensions, is the underlying framework used to apply fuzzy multi-criteria decision making for assessment of reverse logistics (RL) network configurations. To design the sustainable reverse logistics network configuration the manufacturers need to go through a number of trade-offs depending on economical, environmental and social criteria. The various trade-offs can be at collection stage, sorting/testing stage, or processing stage in the RL network. Barker and Zabinsky (2008) from a review of 37 case studies found that the various tradeoffs can be: industry wide collection versus company specific collection, centralized sort-test versus distributed sort-test, original facility processing versus secondary facility processing. Based on these trade-offs there will be eight possible network configurations.

In an early framework developed by Flapper (1996), a number of trade-offs were considered including whether to collect directly from customers or at depots, whether the network should be geographically wide spread or localized, whether the different items should be collected together or separately, whether to transport the return product back to a processing center or recycle the products locally, or whether inspection and sorting should be done immediately or at the point of processing. Fleischmann *et al.* (1997) presented a general framework and discussed the trade-offs such as whether testing and sorting should occur early in the collection process or at the centralized locations, and whether to use traditional supply chain actor or specialized parties. Lau and Wang (2009) considered collection cost, transaction cost and economy of scale as some of the considerations for reverse logistics configuration selection in China. It was also discussed that the outsourcing may help a firm to save cost in the short run, but setting up of own system provides intangible resources, such as enhanced corporate image and capabilities such as expertise in recycling and remanufacturing. Barker and Zabinsky (2011) presented an analytical hierarchy process for network configuration selection by considering cost saving and business relation as the main criteria. But they have not considered the triple bottom line of sustainability (i.e. economical, environmental and social criteria) and uncertainty in reverse logistics. Recycled product, testing cost, scrap shipment and original facility are the sub-criteria considered under the cost saving criteria; and proprietary knowledge and customer interactions are the sub-criteria considered under business relation.

In this chapter, an integrated fuzzy analytic hierarchy process (Fuzzy AHP) and fuzzy technique for order preference by similarity to ideal situation (Fuzzy TOPSIS) is used for the assessment and evaluation of reverse logistics network configurations. With the integration of AHP and TOPSIS, the proposed methodology will have the advantages of both as explained in section 5.3.3. The AHP is used to calculate the criteria weight and TOPSIS is used to find the ranking of alternative network configurations using linguistic variables. However, due to the vagueness and uncertainty on judgments of the decision-maker(s), the crisp pairwise comparison in the conventional AHP and TOPSIS seems to be insufficient and imprecise to capture the right judgments of decision-maker(s). Therefore, linguistic variables along with fuzzy mathematics are used to handle the uncertainty in reverse logistics as explained in section 3.2. The assessment and evaluation of reverse logistics network configurations can help companies to prioritize and develop reverse manufacturing facilities accordingly.

7.2. Model Development

The increasing pressure of sustainable development is forcing the organizations to consider economical, environmental and social factors for the assessment of different reverse logistics network configurations. Different network configurations as discussed in literature review chapter are shown in Table 7.1. Further the assessment and evaluation of alternative network configurations is affected by the economical, environmental and social criteria. The following text provides a discussion on theses network configurations and criteria for their assessment.

Table 7.1: Network configurations in reverse logistics

S. No	Network Configuration	Notation
1	Industry wide collection, centralized sort/test, and original facility processing	A1
2	Industry wide collection, centralized sort/test, and secondary facility processing	A2
3	Industry wide collection, distributed sort/test, and original facility processing	A3
4	Industry wide collection, distributed sort/test, and secondary facility processing	A4
5	Company specific collection, centralized sort/test, and original facility processing	A5
6	Company specific collection, centralized sort/test, and secondary facility processing	A6
7	Company specific collection, distributed sort/test, and original facility processing	A7
8	Company specific collection, distributed sort/test, and secondary facility processing	A8

7.2.1 Alternative network configurations in reverse logistics

Collection, sort/test, and processing are the three fundamental stages of flow in reverse logistics (De Brito *et al.*, 2004; Flapper, 1996; Fleischmann *et al.*, 2004). Based on the these three fundamental stages of flow and a trade-off at each stage, Barker and Zabinsky (2008) constructed eight possible network models as shown in Table 7.1. These trade-off considerations are discussed next.

Collection: Collection systems can be of two types, industry-wide or company specific. In industry-wide collection same type of products from multiple producers are collected within the system. In company-specific collection, company collects its own products only. The benefits of the former are (i) economies of scale due to higher volumes of return and (ii) does not complicate the company's forward supply chain. However, an individual company has limited costing and routing control over this type of collection system. The company-specific collection system tends to strengthen customer relationships, enhance marketing and sales efforts, but transportation costs may be higher.

Sorting/Testing: Sorting/testing can be performed either at a centralized site or at distributed locations. A centralized site is desirable for high-cost testing procedures to minimize costs of testing equipment and specialized labor. But it involves the risk of higher transportation cost as the scrap/waste is identified later, whereas in distributed sorting/testing waste is identified and separated earlier. Distributed sorting/testing sites are often used if low cost testing procedures are available.

Processing: Once the type of processing is determined, the key decision is whether to reprocess at the original facility or at a secondary facility. Processing at the original facility provides increased efficiency from use of original facility equipments and processes. However, it may complicate the production, planning and control of the forward supply chain. The benefits of processing at a secondary facility include economies of scale if done across the entire industry rather than for a single manufacturer.

7.2.2 Criteria for the assessment of network configurations

Assessment of alternative network configurations is affected by various factors. Barker and Zabinsky (2008) in their conceptual framework for reverse logistics discussed different considerations for decision making at each stage of reverse logistics. Degree of producer's control, cost sharing, network simplification, customer relationships, proprietary and intellectual knowledge are some of the factors considered by them. Barker and Zabinsky (2011) in their multi-criteria model considered recycled product, testing cost, scrap shipment and original facility, proprietary knowledge and customer interactions as the six sub-criteria for the selection of network configuration in reverse logistics. The first four criteria – recycled product, testing cost, scrap shipment and original facility – are grouped into cost saving criteria and the last two – proprietary knowledge and customer interactions – are grouped into business relation criteria.

With the increasing pressure for sustainable development organizations needs to consider the different economical, environmental and social factors affecting the selection of network configuration for reverse logistics. Table 7.2 presents the economical, environmental and social criteria and sub-criteria identified with the help of literature review (Barker and Zabinsky, 2008; Barker and Zabinsky, 2011; Nikolaou *et al.*, 2012; Sarkis *et al.*, 2010; Srivastava, 2007; Weeks *et al.*, 2009) and discussion held with experts. These sub-criteria are divided into two categories direct criteria and indirect criteria. The direct criteria mean higher the better (e.g value added recovery, improved customer service, etc.) and indirect criteria mean smaller the better (e.g. processing cost, energy use, etc.).

Figure 7.1 shows the proposed model for the evaluation of alternative network configurations in reverse logistics.

Table 7.2: Criteria for the assessment of network configuration

Criteria	Sub-Criteria	Type
Economical (C1)	Collection and transportation cost (C11)	Indirect
	Sorting/testing cost (C12)	Indirect
	Processing cost (C13)	Indirect
	Value added recovery (C14)	Direct
Environmental (C2)	Energy use (C21)	Indirect
	Effluents or waste generated (C22)	Indirect
	Percentage of products reclaimed (C23)	Direct
Social (C3)	Corporate citizenship and social responsibility (C31)	Direct
	Improved customer service (C32)	Direct
	Intellectual and propriety information (C33)	Direct

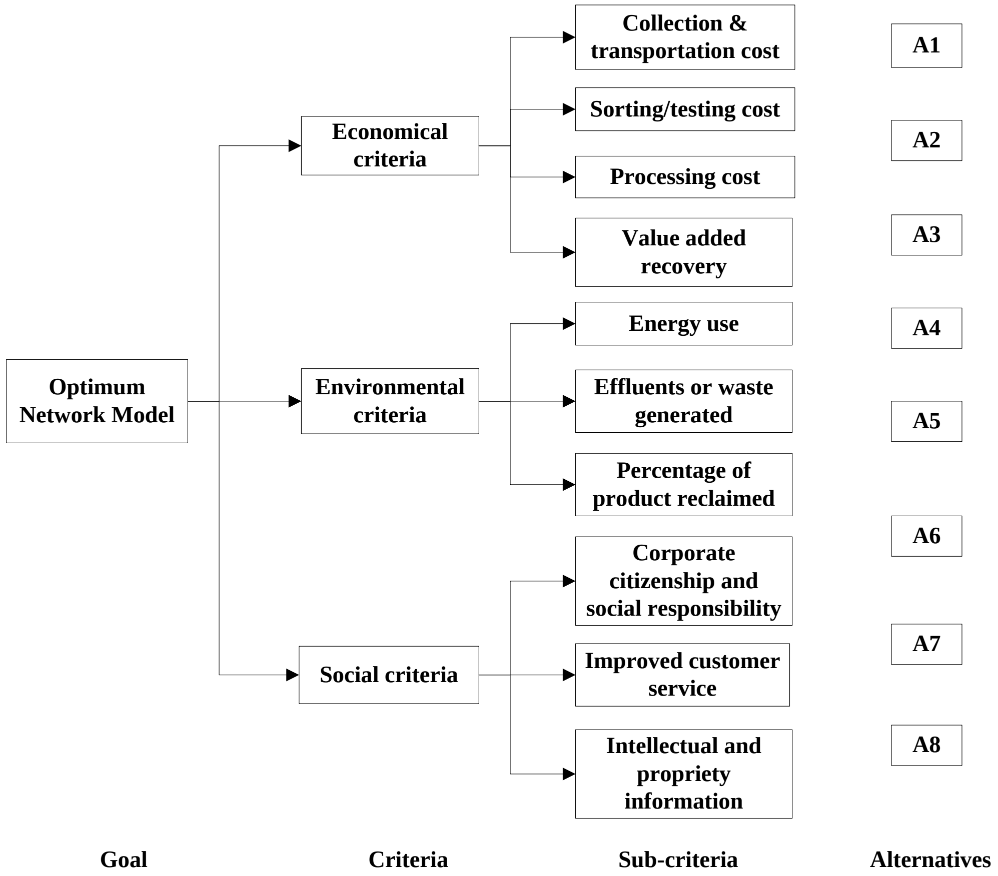

Figure 7.1 Hierarchy for assessment of alternative network configurations in reverse logistics

7.3. Solution Methodology with Illustrative Example

An integrated fuzzy AHP and fuzzy TOPSIS multi-criteria model is proposed for the assessment and evaluation of network configurations in reverse logistics. Fuzzy AHP is used to calculate the criteria weight while fuzzy TOPSIS is used for the ranking of alternative network configurations. The detailed discussion on the selection of MCDM method and the advantages of integrated AHP and TOPSIS is provided in section 5.3. As a case example, network configuration of an Indian automotive sector is taken into consideration. The detailed solution methodology has been provided in section 5.4 and are briefly given below with an illustrative example.

7.3.1 Selection of alternative network configurations in reverse logistics

The first step is to select the alternative network configurations in reverse logistics from literature review and discussion with experts working in the area reverse logistics. The selected alternative network configurations are shown in Table 7.1.

7.3.2 Selection of evaluation criteria

This step involves the selection of economical, environmental and social criteria and sub-criteria for evaluating alternative network configurations The sub-criteria obtained from literature review and discussion held with experts working in the area of supply chain management are – collection and transportation cost (C11), sorting and testing cost (C12), processing cost (C13) and value added recovery (C14), energy use (C21), effluents or waste generated (C22) and percentage of product reclaimed (C23), corporate citizenship and social responsibility (C31), improved customer service (C32) and intellectual and propriety information (C33). Further, these criteria were divided into direct and indirect criteria where direct means more the better (e.g. improved customer service) and indirect means lesser the better (e.g. processing cost) as shown in Table 7.2.

7.3.3 Calculate criteria weights with fuzzy AHP

The AHP method was first introduced by Saaty (1980) and is also known as an eigenvector method. It indicates that the eigenvector corresponding to the largest eigenvalue of the comparison matrix provides the relative priorities of the factors. The hierarchy of product recovery process selection needs to be established before performing the pairwise comparison of AHP, as shown in Figure 7.1. After constructing a hierarchy, the decision-maker(s) makes a pairwise comparison of the elements at a given level to estimate their relative importance in relation to the element at the immediate preceding level. The methodology given by Ayağ and Özdemir (2006) is used to calculate the weight of criteria. The various steps to calculate the criteria weights are mentioned in detail in section 5.4.3 and are briefly given below to elucidate the case example.

***Constructing the fuzzy comparison matrix of criteria**:* The fuzzy comparison matrix for criteria is constructed by the input from experts from the Indian automotive sector. Table 7.3 shows the pairwise comparison of the main criteria using triangular fuzzy numbers. Similarly Table 7.4, Table 7.5 and Table 7.6 shows the pairwise comparison matrix of the economical, environmental and social sub-criteria respectively.

Table 7.3 Fuzzy comparison matrix of the main criteria

	C1	**C2**	**C3**
C1	1	$\tilde{5}$	$\tilde{3}$
C2	$\tilde{5}^{-1}$	1	$\tilde{3}^{-1}$
C3	$\tilde{3}^{-1}$	$\tilde{3}$	1

Table 7.4: Fuzzy comparison matrix of the economical sub-criteria

	C11	**C12**	**C13**	**C14**
C11	1	$\tilde{1}$	$\tilde{1}^{-1}$	$\tilde{5}^{-1}$
C12	$\tilde{1}^{-1}$	1	$\tilde{5}^{-1}$	$\tilde{7}^{-1}$
C13	$\tilde{1}$	$\tilde{5}$	1	$\tilde{1}^{-1}$
C14	$\tilde{5}$	$\tilde{7}$	$\tilde{1}$	1

Table 7.5: Fuzzy comparison matrix of the environmental sub-criteria

	C21	**C22**	**C23**
C21	1	$\tilde{3}$	$\tilde{3}^{-1}$
C22	$\tilde{3}^{-1}$	1	$\tilde{5}^{-1}$
C23	$\tilde{3}$	$\tilde{5}$	1

Table 7.6 Fuzzy comparison matrix of the social sub-criteria

	C31	**C32**	**C33**
C31	1	$\tilde{5}^{-1}$	$\tilde{3}^{-1}$
C32	$\tilde{5}$	1	$\tilde{3}$
C33	$\tilde{3}$	$\tilde{3}^{-1}$	1

Solving for fuzzy eigenvalue: The α-cut fuzzy comparison matrix is generated from the fuzzy comparison matrices (Table 7.3 to 7.6) after substituting $\alpha = 0.5$ in equation (5.7). The α-cut fuzzy comparison matrices are shown in Table 7.7 to 7.10.

Table 7.7 α -cut fuzzy comparison matrix for main criteria

	C1	**C2**	**C3**
C1	1	[4,6]	[2,4]
C2	[1/6,1/4]	1	[1/4,1/2]
C3	[1/4,1/2]	[2,4]	1

Table 7.8: α -cut fuzzy comparison matrix for the economical sub-criteria

	C11	**C12**	**C13**	**C14**
C11	1	[1,2]	[1/2,1]	[1/6,1/4]
C12	[1/2,1]	1	[1/6,1/4]	[1/8,1/6]
C13	[1,2]	[4,6]	1	[1/2,1]
C14	[4,6]	[6,8]	[1,2]	1

Table 7.9 α -cut fuzzy comparison matrix for the environmental sub-criteria

	C21	**C22**	**C23**
C21	1	[2,4]	[1/4,1/2]
C22	[1/4,1/2]	1	[1/6,1/4]
C23	[2,4]	[4,6]	1

Table 7.10 α -cut fuzzy comparison matrix for the social sub-criteria

	C31	**C32**	**C33**
C31	1	[1/6,1/4]	[1/4,1/2]
C32	[4,6]	1	[2,4]
C33	[2,4]	[1/4,1/2]	1

The fuzzy interval values in Tables 7.7 to 7.10 are converted into crisp number by substituting $\mu = 0.5$ in equation (5.8), which is further used to calculate the eigen values as shown in Table 7.11 to 7.14.

Table 7.11 Eigen vector for comparison of main criteria

	C1	**C2**	**C3**	**Priority Vector**
C1	1	5	3	0.6261
C2	0.195	1	0.375	0.1070
C3	0.375	3	1	0.2669
λ_{max} = 3.097, CI= 0.048, CR= 0.083<0.10				

Table 7.12 Eigen vector for comparison of economical sub-criteria

	C11	**C12**	**C13**	**C14**	**Priority Vector**
C11	1	$\tilde{1}$	$\tilde{1}^{-1}$	$\tilde{5}^{-1}$	0.1352
C12	$\tilde{1}^{-1}$	1	$\tilde{5}^{-1}$	$\tilde{7}^{-1}$	0.0729
C13	$\tilde{1}$	$\tilde{5}$	1	$\tilde{1}^{-1}$	0.2927
C14	$\tilde{5}$	$\tilde{7}$	$\tilde{1}$	1	0.4990

λ_{max} = 4.235, CI= 0.078, CR= 0.087<0.10

Table 7.13 Eigen vector for comparison of environmental sub-criteria

	C21	**C22**	**C23**	**Priority Vector**
C21	1	$\tilde{3}$	$\tilde{3}^{-1}$	0.2661
C22	$\tilde{3}^{-1}$	1	$\tilde{5}^{-1}$	0.1097
C23	$\tilde{3}$	$\tilde{5}$	1	0.6240

λ_{max} = 3.126, CI= 0.063, CR= 0.10<=0.10

Table 7.14 Eigen vector for comparison of social sub-criteria

	C31	**C32**	**C33**	**Priority Vector**
C31	1	$\tilde{5}^{-1}$	$\tilde{3}^{-1}$	0.1097
C32	$\tilde{5}$	1	$\tilde{3}$	0.6240
C33	$\tilde{3}$	$\tilde{3}^{-1}$	1	0.2661

λ_{max} = 3.126, CI= 0.063, CR= 0.10<=0.10

Calculating the consistency ratio and consistency index: The eigen values are checked for consistency ratio (CR) using equation 5.10. The CR for the criteria and sub-criteria is under the specified limit of 0.10. The weight of economical, environmental and social criteria are presented by priority vector in Table 7.11; and weight of sub-criteria under these main criteria is presented by priority vector in Tables 7.12, 7.13 and 7.14 respectively. The overall criteria weights of the sub-criteria is obtained by multiplying the priority vector of sub-criteria with the priority vector of corresponding main criteria and is shown in Table 7.15 and are graphically represented in Figure 7.2.

Table 7.15 Overall criteria weight

Criteria	**Sub-criteria**	**Overall criteria weight**
Economical criteria (C1 = 0.6261)	Collection and transportation cost (C11 = 0.1352)	0.0846
	Sorting/testing cost (C12= 0.0729)	0.0456
	Processing cost (C13 = 0.2927)	0.1832
	Value added recovery (C14 = 0.4990)	0.3124
Environmental criteria (C2 = 0.1070)	Energy use (C21 = 0.2661)	0.0285
	Effluents or waste generated (C22 = 0.1097)	0.0117
	Percentage of products reclaimed (C23 = 0.6240)	0.0668
Social criteria (C3 = 0.2669)	Corporate citizenship and social responsibility (C31 = 0.1097)	0.0292
	Improved customer service (C32 = 0.6240)	0.1660
	Intellectual and propriety information (C33 = 0.2661)	0.0708

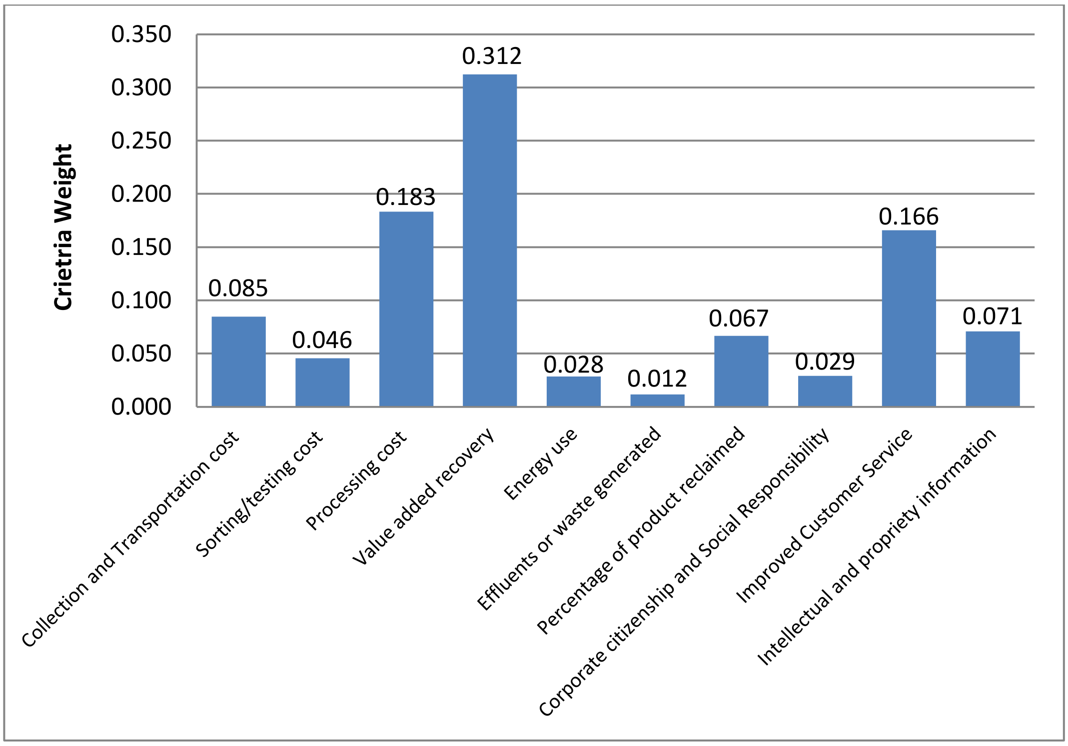

Figure 7.2 Weights for evaluation criteria

7.3.4 Assessment of alternative network configuations with fuzzy TOPSIS

This section presents fuzzy TOPSIS methodology for the assessment and evaluation of alternative network configurations in reverse logistics. The various steps of fuzzy TOPSIS are explained in section 5.4.4 and are briefly given below to elucidate the case example.

***Constructing the fuzzy decision matrix of alternatives**:* After calculating the criteria weights, decision makers provide linguistic ratings for all the alternatives with respect to each criterion, as shown in Table 7.16. This linguistic rating is converted into triangular fuzzy number using Table 5.6 to get fuzzy decision matrix (Table 7.17).

Table 7.16 Linguistic rating of alternatives with respect to each criterion

Criteria →	Economical Criteria				Environmental Criteria			Social Criteria		
Alternatives ↓	C11	C12	C13	C14	C21	C22	C23	C31	C32	C33
A1	L	H	H	L	L	M	L	L	M	L
A2	L	H	L	VL	L	H	L	M	L	VL
A3	L	L	H	L	VL	H	VL	M	L	L
A4	L	M	L	VL	VL	VH	VL	H	VL	VL
A5	H	H	H	VH	M	VL	VH	VL	VH	VH
A6	H	H	L	M	H	L	H	L	M	M
A7	H	M	H	H	L	L	H	L	VH	VH
A8	H	M	L	M	L	M	M	M	M	M

Table 7.17 Fuzzy decision matrix for the alternatives

	A1	A2	A3	A4	A5	A6	A7	A8	a_j^-	c_j^*
C11	(1,3,5)	(1,3,5)	(1,3,5)	(1,3,5)	(5,7,9)	(5,7,9)	(5,7,9)	(5,7,9)	1	9
C12	(5,7,9)	(5,7,9)	(1,3,5)	(3,5,7)	(5,7,9)	(5,7,9)	(3,5,7)	(3,5,7)	1	9
C13	(5,7,9)	(1,3,5)	(5,7,9)	(1,3,5)	(5,7,9)	(1,3,5)	(5,7,9)	(1,3,5)	1	9
C14	(1,3,5)	(1,1,3)	(1,3,5)	(1,1,3)	(7,9,9)	(3,5,7)	(5,7,9)	(3,5,7)	1	9
C21	(1,3,5)	(1,3,5)	(1,1,3)	(1,1,3)	(3,5,7)	(5,7,9)	(1,3,5)	(1,3,5)	1	9
C22	(3,5,7)	(5,7,9)	(5,7,9)	(7,9,9)	(1,1,3)	(1,3,5)	(1,3,5)	(3,5,7)	1	9
C23	(1,3,5)	(1,3,5)	(1,1,3)	(1,1,3)	(7,9,9)	(5,7,9)	(5,7,9)	(3,5,7)	1	9
C31	(1,3,5)	(3,5,7)	(3,5,7)	(5,7,9)	(1,1,3)	(1,3,5)	(1,3,5)	(3,5,7)	1	9
C32	(3,5,7)	(1,3,5)	(1,3,5)	(1,1,3)	(7,9,9)	(3,5,7)	(7,9,9)	(3,5,7)	1	9
C33	(1,3,5)	(1,1,3)	(1,3,5)	(1,1,3)	(7,9,9)	(3,5,7)	(7,9,9)	(3,5,7)	1	9

Table 7.18 Normalized fuzzy decision matrix for the alternatives

	A1	A2	A3	A4	A5	A6	A7	A8
C11	(0.200,0.330,1)	(0.200,0.330,1)	(0.200,0.330,1)	(0.200,0.330,1)	(0.110,0.140,0.200)	(0.110,0.140,0.200)	(0.110,0.140,0.200)	(0.110,0.140,0.200)
C12	(0.110,0.140,0.200)	(0.110,0.140,0.200)	(0.200,0.330,1)	(0.140,0.200,0.330)	(0.110,0.140,0.200)	(0.110,0.140,0.200)	(0.140,0.200,0.330)	(0.140,0.200,0.330)
C13	(0.110,0.140,0.200)	(0.200,0.330,1)	(0.110,0.140,0.200)	(0.200,0.330,1)	(0.110,0.140,0.200)	(0.200,0.330,1)	(0.110,0.140,0.200)	(0.200,0.330,1)
C14	(0.110,0.330,0.550)	(0.110,0.110,0.330)	(0.110,0.330,0.550)	(0.110,0.110,0.330)	(0.780,1,1)	(0.330,0.560,0.780)	(0.550,0.780,1)	(0.330,0.560,0.780)
C21	(0.200,0.330,1)	(0.200,0.330,1)	(0.330,1,1)	(0.330,1,1)	(0.140,0.200,0.330)	(0.110,0.140,0.200)	(0.200,0.330,1)	(0.200,0.330,1)
C22	(0.140,0.200,0.330)	(0.110,0.140,0.200)	(0.110,0.140,0.200)	(0.110,0.110,0.140)	(0.330,1,1)	(0.200,0.330,1)	(0.200,0.330,1)	(0.140,0.200,0.330)
C23	(0.110,0.330,0.550)	(0.110,0.330,0.550)	(0.110,0.110,0.330)	(0.110,0.110,0.330)	(0.780,1,1)	(0.550,0.780,1)	(0.550,0.780,1)	(0.330,0.560,0.780)
C31	(0.110,0.330,0.550)	(0.330,0.560,0.780)	(0.330,0.560,0.780)	(0.550,0.780,1)	(0.110,0.110,0.330)	(0.110,0.330,0.550)	(0.110,0.330,0.550)	(0.330,0.560,0.780)
C32	(0.330,0.560,0.780)	(0.110,0.330,0.550)	(0.110,0.330,0.550)	(0.110,0.110,0.330)	(0.780,1,1)	(0.330,0.560,0.780)	(0.780,1,1)	(0.330,0.560,0.780)
C33	(0.110,0.330,0.550)	(0.110,0.110,0.330)	(0.110,0.330,0.550)	(0.110,0.110,0.330)	(0.780,1,1)	(0.330,0.560,0.780)	(0.780,1,1)	(0.330,0.560,0.780)

Table 7.19 Weighted normalized fuzzy decision matrix for the alternatives

	A1	A2	A3	A4	A5	A6	A7	A8
C11	(0.020,0.030,0.080)	(0.020,0.030,0.080)	(0.020,0.030,0.080)	(0.020,0.030,0.080)	(0.010,0.010,0.020)	(0.010,0.010,0.020)	(0.010,0.010,0.020)	(0.010,0.010,0.020)
C12	(0.010,0.010,0.010)	(0.010,0.010,0.010)	(0.010,0.020,0.050)	(0.010,0.010,0.020)	(0.010,0.010,0.010)	(0.010,0.010,0.010)	(0.010,0.010,0.020)	(0.010,0.010,0.020)
C13	(0.020,0.030,0.040)	(0.040,0.060,0.180)	(0.020,0.030,0.040)	(0.040,0.060,0.180)	(0.020,0.030,0.040)	(0.040,0.060,0.180)	(0.020,0.030,0.040)	(0.040,0.060,0.180)
C14	(0.030,0.100,0.170)	(0.030,0.030,0.100)	(0.030,0.100,0.170)	(0.030,0.030,0.100)	(0.240,0.310,0.310)	(0.100,0.170,0.240)	(0.240,0.310,0.310)	(0.100,0.170,0.240)
C21	(0.010,0.010,0.030)	(0.010,0.010,0.030)	(0.010,0.010,0.030)	(0.010,0.030,0.030)	(0.00,0.010,0.010)	(0.00,0.00,0.010)	(0.010,0.010,0.030)	(0.010,0.010,0.030)
C22	(0.002,0.002,0.004)	(0.001,0.002,0.002)	(0.001,0.002,0.002)	(0.001,0.001,0.002)	(0.004,0.012,0.012)	(0.002,0.004,0.012)	(0.002,0.004,0.012)	(0.002,0.002,0.004)
C23	(0.010,0.020,0.040)	(0.010,0.020,0.040)	(0.010,0.010,0.020)	(0.010,0.010,0.020)	(0.050,0.070,0.070)	(0.040,0.050,0.070)	(0.040,0.050,0.070)	(0.020,0.040,0.050)
C31	(0.00,0.010,0.020)	(0.010,0.020,0.020)	(0.010,0.020,0.020)	(0.020,0.020,0.030)	(0.00,0.00,0.010)	(0.00,0.010,0.020)	(0.00,0.010,0.020)	(0.00,0.020,0.020)
C32	(0.060,0.090,0.130)	(0.020,0.060,0.090)	(0.020,0.060,0.090)	(0.020,0.020,0.060)	(0.130,0.170,0.170)	(0.060,0.090,0.130)	(0.130,0.170,0.170)	(0.060,0.090,0.130)
C33	(0.010,0.020,0.040)	(0.010,0.010,0.020)	(0.010,0.020,0.040)	(0.010,0.010,0.020)	(0.050,0.070,0.070)	(0.020,0.040,0.050)	(0.050,0.070,0.070)	(0.020,0.040,0.050)

Calculating the normalized and weighted normalized matrix*:* After getting the fuzzy decision matrix the next step is to normalize fuzzy decision matrix (Table 7.18) using equation (5.13). The normalized ratings are converted into weighted normalized rating by using equation (5.14) and weights of criteria from Table 7.15. The weighted normalized matrix is shown in Table 7.19.

Calculating the distance of alternatives from fuzzy positive ideal solution (FPIS) and fuzzy negative ideal solution (FNIS)*:* From table 7.19, the distance of each alternative from the FPIS and FNIS is calculated using equation 5.15 and 5.16 respectively. The distance of each alternative from FPIS and FNIS are shown in Table 7.20 and Table 7.21 respectively.

Ranking the alternatives using closeness coefficient*:* After calculating the distance, the next step is to calculate the closeness coefficient (CC_i) using equation (5.19). Closeness coefficient represents the distance of the alternative from the FNIS as a fraction of the total distance from FPIS and FNIS (Table 7.22). Figure 7.3 shows the closeness coefficient values of alternative network configurations with respect to economical, environmental, social, and aggregate perceptive.

Table 7.20 Distance of alternatives from Fuzzy Positive Ideal Solution (FPIS)

	$d_v(A1,A^*)$	$d_v(A2,A^*)$	$d_v(A3,A^*)$	$d_v(A4,A^*)$	$d_v(A6,A^*)$	$d_v(A7,A^*)$	$d_v(A8,A^*)$
C11	0.0509	0.051	0.051	0.051	0.0719	0.072	0.072
C12	0.0388	0.039	0.027	0.036	0.0388	0.039	0.036
C13	0.1556	0.11	0.156	0.11	0.1556	0.11	0.156
C14	0.2158	0.257	0.216	0.257	0.0401	0.15	0.09
C21	0.0171	0.017	0.011	0.011	0.0221	0.024	0.017
C22	0.0091	0.01	0.01	0.01	0.0045	0.009	0.007
C23	0.0461	0.046	0.055	0.055	0.0086	0.019	0.019
C31	0.0202	0.014	0.014	0.008	0.024	0.02	0.02
C32	0.0796	0.115	0.115	0.136	0.0213	0.08	0.021
C33	0.0488	0.058	0.049	0.058	0.0091	0.034	0.009

Table 7.21 Distance of alternatives from Fuzzy Negative Ideal Solution (FNIS)

	d_v(A1,A$^-$)	d_v(A2,A$^-$)	d_v(A3,A$^-$)	d_v(A4,A$^-$)	d_v(A6,A$^-$)	d_v(A7,A$^-$)	d_v(A8,A$^-$)
C11	0.04	0.04	0.045	0.04	0	0	0
C12	0	0	0.024	0.01	0	0	0.01
C13	0.01	0.1	0.01	0.1	0.01	0.1	0.01
C14	0.09	0.04	0.09	0.04	0.26	0.15	0.22
C21	0.02	0.02	0.021	0.02	0	0	0.02
C22	0	0	6E-04	0	0.01	0	0.01
C23	0.02	0.02	0.009	0.01	0.05	0.05	0.05
C31	0.01	0.01	0.014	0.02	0	0.01	0.01
C32	0.08	0.05	0.048	0.02	0.14	0.08	0.14
C33	0.02	0.01	0.02	0.01	0.06	0.03	0.06

Table 7.22 Aggregate closeness coefficient for alternatives

	A1	**A2**	**A3**	**A4**	**A5**	**A6**	**A7**	**A8**
d_i^*	0.682	0.716	0.703	0.732	0.3959	0.557	0.446	0.553
d_i^-	0.290	0.290	0.281	0.270	0.540	0.430	0.510	0.430
CC_i	0.299	0.289	0.285	0.269	0.576	0.433	0.532	0.440

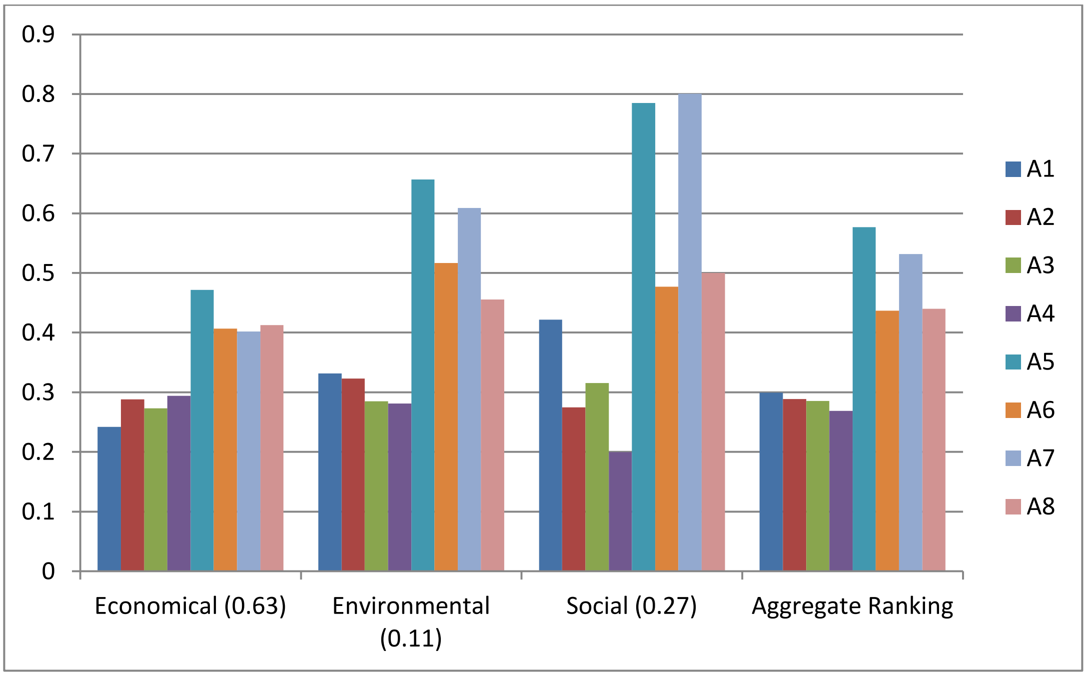

Figure 7.3 Closeness coefficient of alternatives with respect to each and aggregate of criteria

The alternatives are ranked in decreasing order of closeness coefficient (CC_i) and the alternative with the highest closeness coefficient is selected for final implementation. The final ranking of the alternatives is shown in Table 7.23.

Table 7.23 Ranking of alternative network configurations in reverse logistics

Alternative network configurations	Ranking
Company specific collection, centralized sort/test, and original facility processing (A5)	1st
Company specific collection, distributed sort/test, and original facility processing (A7)	2nd
Company specific collection, distributed sort/test, and secondary facility processing (A8)	3rd
Company specific collection, centralized sort/test, and secondary facility processing (A6)	4th
Industry wide collection, centralized sort/test, and original facility processing (A1)	5th
Industry wide collection, centralized sort/test, and secondary facility processing (A2)	6th
Industry wide collection, distributed sort/test, and original facility processing (A3)	7th
Industry wide collection, distributed sort/test, and secondary facility processing (A4)	8th

7.4. Results and Discussion

This chapter presents a fuzzy multi-criteria decision model for the assessment of alternative and evaluation of network configurations in reverse logistics. The illustrative example of automobile company shows that the proposed methodology is able to solve the multi-criteria decision problem for choosing the best network configuration. The results show that economical criterion is having highest weight (0.626) followed by social criteria (0.266) and then environmental criteria (0.107). It shows that in India social and environmental aspects are also taken into consideration but the most important are economical aspects. Further, out of the four sub criteria under economical criterion, value added recovery is having the highest weight. Similarly, the percentage of product reclaimed and improved customer service is having the highest weights under environmental and social criteria respectively.

It is observed from the Figure 7.3 that under the economical and environmental criteria, alternative A5 (company specific collection, centralized sort/test, and original facility processing) is the best network configuration. And under the social criteria alternative A7 (company specific collection, distributed sort/test, and original facility processing) is coming as the best network configuration. But considering the aggregate effect of all the criteria and under the given circumstances alternatives A5 (company specific collection, centralized sort/test, and original facility processing) is the best alternative for automobile reverse logistics network (Figure 7.3). It is also verified as most of automobile remanufacturing case studies are using 'company specific collection, centralized sort/test, and original facility processing' network as presented by Barker and Zabinsky (2008). The results obtained in this study cannot be standardized as these depend on the knowledge, experience, and input of the decision makers. The objective of this study is to provide a robust process for evaluation of reverse logistics network models under the triple bottom line of sustainability.

CHAPTER 8

ASSESSMENT AND EVALUATION OF LITHIUM-ION BATTERY RECYCLING PROCESS - A STUDY

This chapter presents a decision model for the assessment and evaluation of recycling processes for the lithium-ion batteries from electric vehicles. The proposed model has been validated by a case study in Germany.

8.1. Introduction

In last two decades, rapid economic growth of India and China, the most populated countries, has increased the demand of the vehicles in the market. In the major cities of these countries, an increase in the number of vehicles on the roads per day has led to huge environmental degradation in term of air quality and emissions. It has also severely affected the quality of life in these cities. The public has also become aware of the environmental issues affecting them. This has forced the governments to introduce stringent emission regulations for the vehicles (Badami, 2005; Pucher *et al.*, 2005). The automobile manufacturers are not only trying to comply with these ever changing regulations but also working hard to beat the competition among themselves. Environment friendly vehicles provide an edge over competitors. In addition to this, the increasing prices of fossil fuels and the political implications of fossil fuel dependency on few countries have made the governments and manufacturers to think about vehicles with alternative fuel. The number of electric vehicles in recent years has increased and this trend will continue. For example, the German government has aimed at a market penetration of one million plug-in hybrid electric vehicles (PHEVs) and battery electric vehicles (BEVs) by 2020 (Nemry and Brons, 2010). An essential component of such vehicles is the lithium-ion battery (LiB) which has high specific power, high energy density and long life. The primary nonferrous resources required for the manufacturing of these batteries are copper, cobalt, nickel, and lithium. Unfortunately, these resources are also scarce and some of them like cobalt and lithium are available only in few countries. According to U. S. Geological Survey (2010), seven countries account for 85% of the world's production of mined cobalt and lithium (Hoyer *et al.*, 2011). Recycling of LiB needs to be focused on due to scarcity of the resources used in the production of these batteries. The increasing environmental degradation, fossil fuel prices and political implications of fossil fuel dependency have increased the demand of electric vehicles with lithium-ion batteries. However, the increasing demand of lithium-ion batteries also increases the demand for its recycling. The selection of recycling process for these batteries is a complex problem. The alternative recycling processes have to be evaluated with respect to different criteria like energy consumption, material recovery, environmental impact, health & safety, processing time, degree of flexibility initial investment and labor cost. Recycling will provide economic benefits and lessen the dependency on the countries producing cobalt and lithium.

There are few processes for recycling of portable lithium-ion batteries with the primary objective of cobalt recovery. However, the chemistry in lithium-ion batteries intended for vehicle applications is quite different (Ekermo, 2009). Portable LiB use lithium cobalt oxide (LCO), which offers high energy density, but have well-known safety concerns, especially when damaged. However, vehicle batteries use lithium iron phosphate (LFP), lithium manganese oxide (LMO) and lithium nickel manganese cobalt oxide (NMC), which offer lower energy density, but longer lives and inherent safety. Hereafter, in this chapter LiB means the lithium-ion batteries used in vehicles. In general, disassembly, mechanical conditioning, pyrometallurgy, and hydrometallurgy are used in recycling of LiB to separate the different non-iron metals and other materials from each other. These four processes are usually used in the combination of two or more to recycle or recover the main components from spent LiBs (Hoyer *et al.*, 2011; Kwade, 2010).

The evaluation is a major hurdle in the justification and selection of any multifaceted process. The evaluation of alternatives for battery recycling is a multifaceted problem and these are to be evaluated on the bases of various criteria. Traditional economic evaluation techniques require hard core quantitative data that may be difficult to retrieve; hence it may be highly inappropriate to apply these techniques for the multifaceted problems. To overcome this dilemma, a multi-criteria decision model has been proposed for the evaluation of alternative lithium-ion battery recycling processes. The selection of best alternative combination depends on many potential criteria such as energy consumption, material recovery, environmental impact, health & safety, processing time and degree of flexibility (Hoyer *et al.*, 2011). Further, a lot of uncertainties are related to input, output and processes of recycling. Input related uncertainties can be classified into quantity, spatial distribution and specification of the battery returns. Output related uncertainties can be related to product reuse, component reuse and material reuse opportunities. Process related uncertainties exist with respect to optimal combination and configuration of processes (Hoyer *et al.*, 2011). It is well known that fuzzy logic is the best way to deal with uncertainty and vagueness (Karimi *et al.*, 2011).

This chapter presents an integrated multi-criteria decision model comprising fuzzy technique for order preference by similarity to ideal solution (Fuzzy TOPSIS) and fuzzy analytical hierarchical process (Fuzzy AHP) to evaluate and select the best recycling process for lithium-ion batteries. The model has been validated by a case study with the help of four German industrial experts involved in the recycling of lithium-ion batteries. It is expected that the proposed model will provide the decision makers/managers sufficient confidence for evaluation of alternative recycling processes for lithium-ion batteries to select the best alternative under the given circumstances.

8.2. Background

Lithium-ion batteries are rechargeable batteries with promising properties for electric mobility due to their high power density and specific energy (Hoyer *et al.*, 2011). Lithium-ion battery cells consist of a cathode, an anode, a separator, an electrolyte, and a casing. Cathode and anode conductors are usually made of aluminium and copper foils respectively. The cathode is coated with either a mix of lithium or other metals like cobalt, nickel, manganese, and aluminium (LiMeO2) or lithium-iron-phosphate (LiFePO4). The anode is usually coated with either graphitic or amorphous carbon or lithium-alloying metals (Shukla and Kumar, 2008). Recycling processes for lithium-ion batteries are classified into disassembly, mechanical conditioning, hydrometallurgical conditioning and pyrometallurgical conditioning (Hoyer *et al.*, 2011; Kwade, 2010). These four processes are used in combination with each other as discussed later in this section.

Disassembly: In disassembly, battery systems are broken down to module and cell level, a prerequisite for remanufacturing of batteries. Reusable components and large material fractions, e.g. the battery casing and electronics are separated before further conditioning (Hoyer *et al.*, 2011). Being a manual process it requires high expenditure on labor. Scarce metals like cobalt, nickel and lithium cannot be separated and recovered by disassembly alone.

Mechanical conditioning: In mechanical conditioning, materials of the cells are separated by different comminuting, sizing and concentration processes like crushing, screening and magnetic separation (Hoyer *et al.*, 2011). Mechanical separation processes cannot separate all components in spent LiB as these are composed of several metals, organic substances, and inorganic substances which penetrate into each other. These materials are present in small volumes with accurate, fine and complicated structure, therefore, these components are difficult to separate from each other by mechanical separation processes (Xu *et al.*, 2008). Mechanical conditioning can recover copper and aluminium but scarce metals like cobalt, nickel and lithium cannot be recovered. But it could be a necessary preparation for subsequent recovery.

Pyrometallurgical conditioning: Pyrometallurgical conditioning is the thermal treatment of the materials at high temperatures. Pyrometallurgy of LiB can be easily combined with the production of steel and other ferromanganese alloys (Hoyer *et al.*, 2011). Thermal treatment has the advantage of having simple and convenient operations. However, in this technique, it is not possible to recover organic compounds as these get burnt. Costly equipments for purifying the smoke and gas resulting from combustion of carbon and organic compounds need to be installed. It is the most commonly used process because of its relative simplicity (Kwade, 2010).

Hydrometallurgical conditioning: Hydrometallurgical conditioning typically combines leaching, solution concentration and purification (Hoyer *et al.*, 2011). The hydrometallurgical process is generally used to recover non-ferrous metals from active materials after mechanical conditioning or from the slag of pyrometallurgical process. Although it separates lithium from other components but it is a complex and costly process.

As lithium-ion batteries consist of a variety of different materials, a single recycling process alone can recover only a part of these components. Therefore, a combination of different recycling processes is necessary to recycle or recover all the relevant materials from spent LiBs (Xu *et al.*, 2008). Several recycling process chains have been developed for the recycling of portable lithium-ion batteries with the primary objective of cobalt recovery (Lupi *et al.*, 2005). However, the chemistry in lithium-ion batteries intended for vehicle applications is quite different. The weight of a vehicle battery ranges from 30 to 300 kg but the battery from a laptop computer weighs only about 300 grams. Thus, the potential hazards of dismantling are very different. In order to be well prepared for end-of-life treatment of the batteries, new recycling process combinations must be developed for vehicle lithium-ion batteries. Figure 8.1 shows different process combination possibilities and the resultant recovered materials. Each combination has its advantages and disadvantages based on potential criteria like energy consumption, material recovery, environmental impact, health & safety, processing time, degree of flexibility, initial investment, and labor cost (Hoyer *et al.*, 2011). Therefore, an integrated fuzzy multi criteria decision model is developed to evaluate various lithium-ion battery recycling process alternatives.

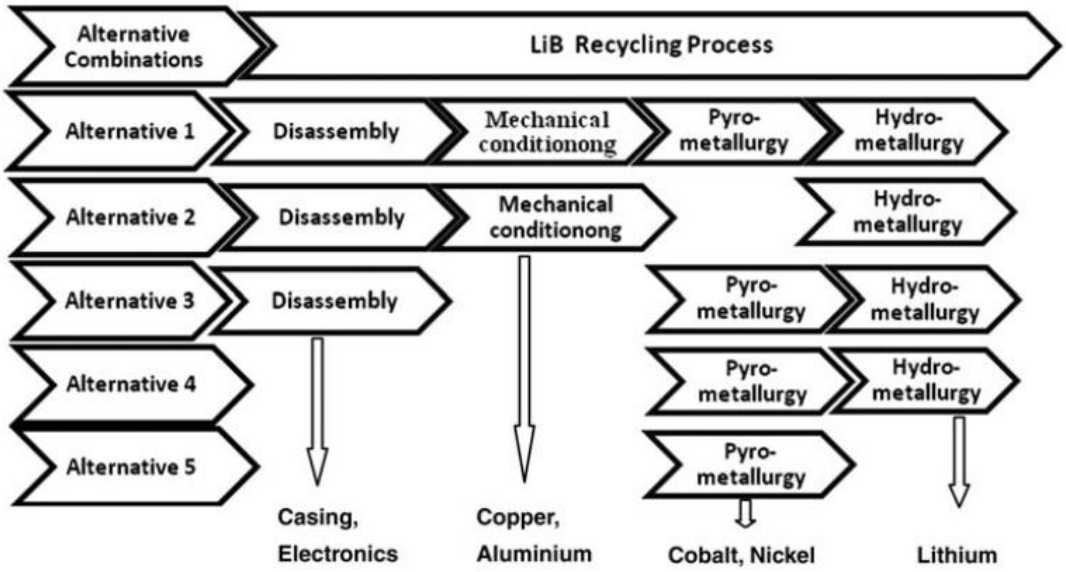

Figure 8.1 Possible alternative combinations of recycling processes; adopted from Hoyer *et al.* (2011)

8.3. Methodology for the Assessment of LiB Recycling Processes

An integrated Fuzzy AHP and Fuzzy TOPSIS approach is proposed for the evaluation of recycling processes of lithium-ion batteries. Fuzzy AHP is used to calculate the criteria weights and Fuzzy TOPSIS is used to rank the alternatives. The detailed discussion on the selection of MCDM method and the advantages of integrated AHP and TOPSIS has been provided in section 5.3. This section presents a case study to evaluate the lithium-ion battery recycling alternatives with the help of four German experts involved in the recycling of LiBs. However, to retain confidentiality the names and organizations are not mentioned. The various steps of the proposed methodology are presented here.

8.3.1 Selection of recycling alternatives

The first step is to select the alternative process combinations for the recycling of lithium-ion batteries from literature review and discussion with recycling experts. Five selected alternatives as shown in Figure 8.1 are: disassembly-mechanical conditioning-pyrometallurgy-hydrometallurgy combination (A1), disassembly-mechanical conditioning-hydrometallurgy combination (A2), disassembly-pyrometallurgy-hydrometallurgy combination (A3), pyrometallurgy-hydrometallurgy combination (A4), and pyrometallurgy (A5).

8.3.2 Selection of recycling criteria

This step involves the selection of criteria for evaluating alternative recycling process combinations. These criteria are obtained from literature review (Hoyer *et al.*, 2011; Patil *et al.*; Shukla and Kumar, 2008; Xu *et al.*, 2008) and discussion held with recycling experts. Eight criteria selected for the present problem are given in Table 8.1. Further, these criteria were divided into direct and indirect criteria where direct means more the better (e.g. degree of flexibility) and indirect means lesser the better (e.g. cost).

Table 8.1 Criteria influencing recycling process

Criteria	Criteria Type
Initial Investment (C1)	Indirect
Labour Cost (C2)	Indirect
Energy Consumption (C3)	Indirect
Material Recovery (C4)	Direct
Environmental Impact (C5)	Indirect
Health & Safety (C6)	Direct
Processing Time (C7)	Indirect
Degree of Flexibility (C8)	Direct

8.3.3 Selection of fuzzy linguistic variables and membership functions

In fuzzy set theory, conversion scales are applied to transform the linguistic terms into fuzzy numbers. In this model, a scale of 1–9 is used for rating the criteria and the alternatives. Table 8.2 presents the linguistic variables and membership functions for the alternatives and criteria (Önüt *et al.*, 2008). The membership functions are expressed via the triangular fuzzy numbers (TFN) in order to represent the relative importance among the criteria (Zhu *et al.*, 1999). The other advantages of using the TFN are presented in chapter 3 (Section 3.2.4). A TFN is fully characterized by a triple real number (a, b, c), where parameter ‘b’ gives the maximal grade of the membership function μ(x), and parameters ‘a’ and ‘c’ are the lower and upper bounds that limit the field of the possible evaluation. The TFN membership is calculated as shown in equation 8.1.

$$\mu(x) = \begin{cases} (x-a)/(b-a), & x\varepsilon[a,b] \\ (c-x)/(c-b), & x\varepsilon[b,c] \\ 0 & otherwise \end{cases} \tag{8.1}$$

Let us assume there are m possible alternatives A_i $(i = 1, 2 \ldots m)$ which are to be evaluated against n criteria C_j $(j = 1, 2 \ldots n)$. The criteria weights are denoted by w_j $(j = 1, 2 \ldots n)$. The performance ratings of each decision maker d_k $(k = 1, 2 \ldots K)$, for each alternative A_i with respect to criteria C_j are denoted by $\widetilde{D}_k = \widetilde{x}_{ijk} (i = 1,2.....m;\ j = 1,2....n;\ k = 1,2....K)$ with membership function $\mu(x)$.

Table 8.2 Linguistic terms and fuzzy ratings for the alternatives and criteria

Linguistic terms for alternative ratings		**Linguistic terms for criteria ratings**	
Linguistic Term	Triangular Fuzzy Scale (a,b,c)	Linguistic Term	Triangular Fuzzy Scale (a,b,c)
Very poor (VP)	(1,1,3)	Very Low (VL)	(1,1,3)
Poor (P)	(1,3,5)	Low (L)	(1,3,5)
Fair (F)	(3,5,7)	Medium (M)	(3,5,7)
Good (G)	(5,7,9)	High (H)	(5,7,9)
Very Good (VG)	(7,9,9)	Very High (VH)	(7,9,9)

8.3.4 Calculation of criteria weight with fuzzy AHP

The methodology given by Chang (1996) is used to find the criteria weight using fuzzy mathematics in conjunction with AHP. The steps of fuzzy AHP as are follows:

Step i: Each expert/decision-maker (D_k), individually carry out pairwise comparison between selected criteria as given below:

$$\tilde{D}k = \begin{array}{c} \\ C1 \\ C2 \\ . \\ . \\ Cn \end{array} \begin{array}{cccccc} C1 & C2 & . & . & . & Cn \\ \left[\begin{matrix} x_{11k} \\ x_{21k} \\ . \\ . \\ x_{n1k} \end{matrix}\right. & \begin{matrix} x_{12k} \\ \\ \\ \\ x_{n2k} \end{matrix} & \begin{matrix} . \\ \\ \\ \\ \\ \end{matrix} & & \begin{matrix} . \\ \\ \\ \\ \\ \end{matrix} & \left.\begin{matrix} x_{1nk} \\ \\ \\ \\ x_{nnk} \end{matrix}\right] \end{array}$$

The pair-wise comparison of four decision-makers for the eight criteria is as:

$$\tilde{D}1 = \begin{bmatrix} 1 & 1/3 & 1/3 & 1/7 & 1/5 & 1/5 & 1/3 & 1/3 \\ 3 & 1 & 2 & 3 & 1/5 & 1/5 & 1/3 & 1/3 \\ 3 & 1/2 & 1 & 1 & 1 & 1/5 & 3 & 5 \\ 7 & 1/3 & 1 & 1 & 1 & 1/5 & 5 & 3 \\ 5 & 5 & 1 & 1 & 1 & 1/3 & 5 & 5 \\ 5 & 5 & 5 & 5 & 3 & 1 & 5 & 5 \\ 3 & 1/3 & 1/3 & 1/5 & 1/5 & 1/5 & 1 & 1/3 \\ 3 & 1/5 & 1/5 & 1/3 & 1/5 & 1/5 & 3 & 1 \end{bmatrix} \quad \tilde{D}2 = \begin{bmatrix} 1 & 1/5 & 1/5 & 1/7 & 1/7 & 1/9 & 1/3 & 1/7 \\ 5 & 1 & 1 & 3 & 1/2 & 1/3 & 3 & 1 \\ 5 & 1 & 1 & 2 & 2 & 1/3 & 3 & 1 \\ 7 & 1/3 & 1/2 & 1 & 1 & 3 & 1/3 & 3 \\ 7 & 2 & 1/2 & 1 & 1 & 3 & 1/3 & 3 \\ 9 & 3 & 3 & 1/3 & 1/3 & 1 & 5 & 1/3 \\ 3 & 1/3 & 1/3 & 3 & 3 & 1/5 & 1 & 1/3 \\ 7 & 1 & 1 & 1/3 & 1/3 & 1/5 & 3 & 1 \end{bmatrix}$$

$$\tilde{D}3 = \begin{bmatrix} 1 & 1/3 & 1 & 1 & 1/5 & 1/9 & 1/3 & 1/3 \\ 3 & 1 & 1 & 1 & 1/5 & 1/9 & 5 & 5 \\ 1 & 1 & 1 & 1 & 1 & 1 & 3 & 5` \\ 1 & 1 & 1 & 1 & 1/3 & 1/9 & 5 & 5 \\ 5 & 5 & 1 & 3 & 1 & 1 & 5 & 5 \\ 9 & 9 & 1 & 9 & 1 & 1 & 9 & 9 \\ 3 & 1/5 & 1/3 & 1/5 & 1/5 & 1/9 & 1 & 3 \\ 3 & 1/5 & 1/5 & 1/5 & 1/5 & 1/9 & 1/3 & 1 \end{bmatrix} \quad \tilde{D}4 = \begin{bmatrix} 5 & 1/5 & 1/3 & 1/9 & 1/9 & 1/3 & 3 & 1/7 \\ 5 & 1 & 3 & 1/7 & 1/7 & 3 & 5 & 1/5 \\ 3 & 1/3 & 1 & 1/9 & 1/7 & 1 & 5 & 1/5 \\ 9 & 7 & 9 & 1 & 3 & 5 & 9 & 5 \\ 9 & 7 & 7 & 1/3 & 1 & 5 & 9 & 3 \\ 3 & 1/3 & 1 & 1/5 & 1/5 & 1 & 5 & 1/5 \\ 1/3 & 1/5 & 1/5 & 1/9 & 1/9 & 1/5 & 1 & 1/9 \\ 7 & 5 & 5 & 1/5 & 1/3 & 5 & 9 & 1 \end{bmatrix}$$

Next, the above pairwise comparisons of all decision makers are integrated into TFN matrix using equation 8.2. The fuzzy decision matrix is shown in Table 8.3.

$$a = \min_k \{x_{nnk}\}, \quad b = 1/K \times \Sigma_{k=1}^{k=K} x_{nnk} \quad \text{and} \quad c = \max_k \{x_{nnk}\} \qquad (8.2)$$

Step ii: Next, determine the fuzzy priority weights of all criteria by using extent analysis (Chang, 1996). In the method, the “extent” is quantified by using a fuzzy number. According to the extent analysis method, each object could be taken to perform extent analysis for each goal respectively. On the basis of the fuzzy values for the extent analysis of each object, a fuzzy synthetic degree value can be obtained, which is defined by equation 8.3.

$$S_{ci} = \Sigma_{j=1}^{j=n} M_{gi}^{j} \otimes \left[\Sigma_{i=1}^{m} \Sigma_{j=1}^{n} M_{gi}^{j}\right]^{-1}, \qquad (8.3)$$

where S_{ci} is fuzzy synthetic extent with respect to i^{th} criterion and $M_{gi}^{j} (j = 1,2...n)$ are triangular fuzzy numbers. The fuzzy synthetic extents of the eight criteria computed using equation 8.3 is as follows:

S_{c1}= (0.009, 0.020, 0.130)	S_{c2}= (0.033, 0.120, 0.470)
S_{c3}= (0.023, 0.099, 0.400)	S_{c4}= (0.026, 0.180, 0.950)
S_{c5}= (0.049, 0.197, 0.849)	S_{c6}= (0.042, 0.212, 0.996)
S_{c7}= (0.009, 0.049, 0.256)	S_{c8}= (0.020, 0.108, 0.603)

Table 8.3 Fuzzy evaluation matrix

	C1	**C2**	**C3**	**C4**	**C5**	**C6**	**C7**	**C8**
C1	(1,1,1)	(0.2,0.26,0.33)	(0.2,0.46,1)	(0.11,0.34,1)	(0.11,0.16,0.2)	(0.11,0.18,0.33)	(0.33,1,3)	(0.14,0.23,0.33)
C2	(3,4,5)	(1,1,1)	(1,1.75,3)	(0.14,1.78,3)	(0.14,0.26,0.5)	(0.11,0.91,3)	(3,4,5)	(0.2,2.8,5)
C3	(1,3,5)	(0.33,0.70,1)	(1,1,1)	(0.11,1.02,2)	(0.14,1.03,2)	(0.2,0.63,1)	(3,3.5,5)	(0.2,2.8,5)
C4	(1,6,9)	(0.33,2.16,7)	(0.5,2.87,9)	(1,1,1)	(0.33,1.33,3)	(0.11,3.07,9)	(0.33,4.8,9)	(3,4,5)
C5	(5,6.5,9)	(2,4.75,7)	(0.5,2.37,7)	(0.33,1.33,3)	(1,1,1)	(0.33,2.33,5)	(0.33,4.8,9)	(3,4,5)
C6	(3,6.5,9)	(0.33,3.66,9)	(1,2.5,5)	(0.11,3.61,9)	(0.2,1.13,3)	(1,1,1)	(5,6,9)	(0.2,4.8,9)
C7	(0.33,2.33,3)	(0.2,0.26,0.33)	(0.2,0.3,0.33)	(0.11,0.87,3)	(0.11,0.87,3)	(0.11,0.17,0.2)	(1,1,1)	(0.11,0.94,3)
C8	(3,5,7)	(0.2,1.6,5)	(0.2,1.6,5)	(0.2,0.26,0.33)	(0.2,0.26,0.33)	(0.11,1.37,5)	(0.33,3.8,9)	(1,1,1)

Table 8.4 Fuzzy value comparison for all criteria

V($S_{c1} \geq S_{c2}$) = 0.51	**V($S_{c1} \geq S_{c3}$) = 0.59**	**V($S_{c1} \geq S_{c4}$) = 0.4**	**V($S_{c1} \geq S_{c5}$) = 0.32**	**V($S_{c1} \geq S_{c6}$) = 0.32**	**V($S_{c1} \geq S_{c7}$) = 0.84**	**V($S_{c1} \geq S_{c8}$) = 0.57**
V($S_{c2} \geq S_{c1}$) = 1	V($S_{c2} \geq S_{c3}$) = 1	V($S_{c2} \geq S_{c4}$) = 0.87	V($S_{c2} \geq S_{c5}$) = 0.84	V($S_{c2} \geq S_{c6}$) =0.82	V($S_{c2} \geq S_{c7}$) = 1	V($S_{c2} \geq S_{c8}$) = 1
V($S_{c3} \geq S_{c1}$) = 1	V($S_{c3} \geq S_{c2}$) = 0.94	V($S_{c3} \geq S_{c4}$) = 0.81	V($S_{c3} \geq S_{c5}$) = 0.78	V($S_{c3} \geq S_{c6}$) = 0.76	V($S_{c3} \geq S_{c7}$) = 1	V($S_{c3} \geq S_{c8}$) = 1
V($S_{c4} \geq S_{c1}$) = 1	V($S_{c4} \geq S_{c2}$) = 1	V($S_{c4} \geq S_{c3}$) = 1	V($S_{c4} \geq S_{c5}$) = 0.98	V($S_{c4} \geq S_{c6}$) = 0.97	V($S_{c4} \geq S_{c7}$) = 1	V($S_{c4} \geq S_{c8}$) = 1
V(Sc5 ≥Sc1) = 1	V(Sc5 ≥Sc2) = 1	V(Sc5 ≥Sc3) = 1	V(Sc5 ≥Sc4) = 1	V(Sc5 ≥Sc6) = 0.98	V(Sc5 ≥Sc7) = 1	V(Sc5 ≥Sc8) = 1
V(Sc6 ≥Sc1) = 1	V(Sc6 ≥Sc2) = 1	V(Sc6 ≥Sc3) = 1	V(Sc6 ≥Sc4) = 1	V(Sc6 ≥Sc5) = 1	V(Sc6 ≥Sc7) = 1	V(Sc6 ≥Sc8) = 1
V(Sc7 ≥Sc1) = 1	V(Sc7 ≥Sc2) = 0.75	V(Sc7 ≥Sc3) = 0.82	V(Sc7 ≥Sc4) = 0.63	V(Sc7 ≥Sc5) = 0.58	V(Sc7 ≥Sc6) = 0.56	V(Sc7 ≥Sc8) = 0.79
V(Sc8 ≥Sc1) = 1	V(Sc8 ≥Sc2) = 0.98	V(Sc8 ≥Sc3) = 1	V(Sc8 ≥Sc4) = 0.88	V(Sc8 ≥Sc5) = 0.86	V(Sc8 ≥Sc6) = 0.84	V(Sc8 ≥Sc7) = 1

Step iii: Next, compare the degree of possibility of $S_{c2} \geq S_{c1}$. As $S_{c1} = (l_1, m_1, u_1)$ and $S_{c2} = (l_2, m_2, u_2)$ are two triangular fuzzy numbers, therefore the degree of possibility of $S_{c2} \geq S_{c1}$ is defined by equation 8.4.

$$V(S_{c2} > S_{c1}) = \begin{cases} 1, & m_2 \geq m_1 \\ 0, & l_1 \geq u_2 \\ (l_1 - u_2)/[(m_2 - u_2) - (m_1 - l_1)], & otherwise \end{cases} \tag{8.4}$$

The degree of possibility of each criterion with respect to all criteria is shown in Table 8.4

Step iv: Find the priority weight for criteria using minimum operator.

To compare S_{c1} and S_{c2}, both the values of $V(S_{c1} \geq S_{c2})$ and $V(S_{c2} \geq S_{c1})$ are needed.

The degree of possibility for a convex fuzzy number to be greater than k convex fuzzy numbers S_{cj} $(j = 1, 2 \ldots k)$ is given by equation 8.5.

$$\min V(S_c \geq S_{ci}), \qquad j = 1, 2 \ldots\ldots k \tag{8.5}$$

The defuzzified or crisp value of each criterion weight is given by equation 8.6.

$$d'(C_j) = \min V(S_i \geq S_k) \text{ for } k = 1, 2 \ldots\ldots m;\ k \neq j \tag{8.6}$$

The crisp values of criteria weight using above equation are:

$d'(C_1) = 0.32$; $d'(C_2) = 0.82$; $d'(C_3) = 0.76$; $d'(C_4) = 0.97$;

$d'(C_5) = 0.98$; $d'(C_6) = 1$; $d'(C_7) = 0.56$; and $d'(C_8) = 0.84$

The weight vector is given by equation 8.7.

$$W' = [d'(C_1), d'(C_2) \ldots\ldots d'(C_n)]^T \tag{8.7}$$

$$= [0.32, 0.82, 0.76, 0.97, 0.98, 1, 0.56, 0.84]^T$$

Step v: The normalized weight for criteria are computed as given in equation 8.8.

$$W = [d(C_1), d(C_2) \ldots\ldots d(C_n)]^T \tag{8.8}$$

Hence the defuzzified or crisp weights for the eight criteria are shown in Figure 8.2.

W= [0.052, 0.131, 0.122, 0.155, 0.156, 0.159, 0.09, 0.134]

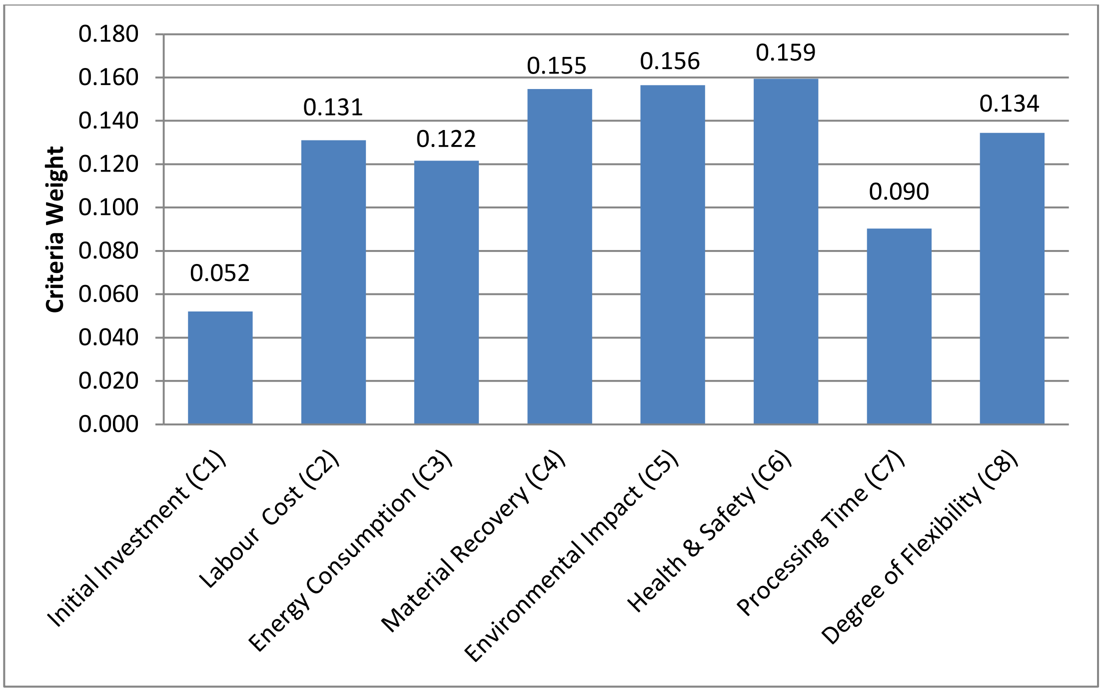

Figure 8.2 Weights for evaluation criteria

8.3.5 Assessment of LiB recycling processes with fuzzy TOPSIS

This section presents a fuzzy TOPSIS model, developed for the assessment and evaluation of LiB recycling processes using fuzzy mathematics in conjunction with TOPSIS. The various steps of the model are:

Step i: Assignment of rating to the alternatives

First each decision maker gives linguistic rating for the recycling alternatives. Table 8.5 shows the linguistic rating of each alternative by all decision makers with respect to all criteria. In this case study there are five alternatives, eight criteria and four decision makers.

Step ii: Compute aggregate fuzzy ratings for the alternatives

The fuzzy ratings of all decision makers are described as triangular fuzzy numbers $\tilde{x}_k = (l_k, m_k, u_k)$, k = 1, 2. . . K, and the aggregated fuzzy rating is given by $\tilde{x} = (a, b, c)$ where

$$a = \min_k \{l_k\}, \quad b = 1/K \times \Sigma_{k=1}^{k=K} \{m_k\}, \quad c = \min_k \{u_k\}$$

The aggregate fuzzy ratings of alternatives are shown in last column of Table 8.5.

Table 8.5 Aggregate fuzzy rating for the alternatives

Criteria	Alternatives	Decision Makers				Aggregate Fuzzy Rating
		D1	D2	D3	D4	
Initial Investment	A1	VP	VP	P	VP	(1,1.5,5)
	A2	P	F	P	VP	(1,2.5,5)
	A3	P	P	F	VP	(1,3,7)
	A4	P	P	F	P	(1,3.5,7)
	A5	P	F	F	P	(1,4,7)
Labour Cost	A1	P	VP	P	VP	(1,2,5)
	A2	P	P	P	VP	(1,2.5,5)
	A3	P	F	P	P	(1,3.5,7)
	A4	G	F	G	G	(3,6.5,9)
	A5	G	F	G	VG	(3,7,9)
Energy Consumption	A1	VP	VP	G	VP	(1,2,7)
	A2	VP	VP	P	G	(1,2.5,7)
	A3	P	F	F	VP	(1,3,7)
	A4	F	P	F	VP	(1,3.5,7)
	A5	P	F	F	P	(1,4,7)
Material Recovery	A1	VG	VG	G	VG	(5,8.5,9)
	A2	VG	G	G	VG	(5,8,9)
	A3	G	G	F	G	(3,6.5,9)
	A4	F	G	F	G	(3,6,9)
	A5	VP	F	P	P	(1,3,7)
Environmental Impact	A1	F	P	G	P	(1,4.5,9)
	A2	G	F	G	G	(3,6.5,9)
	A3	F	P	G	P	(1,4.5,9)
	A4	P	F	F	P	(1,4,7)
	A5	P	P	VP	VP	(1,2.5,5)
Health & Safety	A1	P	P	F	F	(1,4,7)
	A2	P	P	F	G	(1,4.5,9)
	A3	G	F	F	P	(1,5,9)
	A4	G	G	G	P	(1,6,9)
	A5	G	G	G	P	(1,6,9)
Processing Time	A1	VP	VP	F	VP	(1,2,7)
	A2	P	P	F	VP	(1,3,7)
	A3	P	F	F	P	(1,4,7)
	A4	G	F	G	F	(3,6,9)
	A5	VG	G	G	F	(3,7,9)
Degree of Flexibility	A1	VG	VG	G	VG	(5,8.5,9)
	A2	VG	G	G	F	(3,7,9)
	A3	G	G	G	G	(5,7,9)
	A4	F	G	F	G	(3,6,9)
	A5	P	F	P	G	(1,4.5,9)

Step iii: Compute the fuzzy decision matrix

The aggregate fuzzy rating of alternative processes with respect to each criterion (i.e. Table 8.5), is represented by fuzzy decision matrix $(\tilde{D})$ as shown in Table 8.6.

Table 8.6 Fuzzy decision matrix for the alternatives

	C1	**C2**	**C3**	**C4**	**C5**	**C6**	**C7**	**C8**
A1	(1,1.5,5)	(1,2,5)	(1,2,7)	(5,8.5,9)	(1,4.5,9)	(1,4,7)	(1,2,7)	(5,8.5,9)
A2	(1,2.5,5)	(1,2.5,5)	(1,2.5,7)	(5,8,9)	(3,6.5,9)	(1,4.5,9)	(1,3,7)	(3,7,9)
A3	(1,3,7)	(1,3.5,7)	(1,3,7)	(3,6.5,9)	(1,4.5,9)	(1,5,9)	(1,4,7)	(5,7,9)
A4	(1,3.5,7)	(3,6.5,9)	(1,3.5,7)	(3,6,9)	(1,4,7)	(1,6,9)	(3,6,9)	(3,6,7)
A5	(1,4,7)	(3,7,9)	(1,4,7)	(1,3,7)	(1,2.5,5)	(1,6,9)	(3,7,9)	(1,4.5,9)

Step iv: Normalize the fuzzy decision matrix

The fuzzy decision matrix (Table 8.6) is normalized using a linear scale transformation to bring the various criteria scales to a comparable scale. The normalized fuzzy decision matrix $\tilde{R}$ is given by equation 8.9. The normalized fuzzy decision matrix is shown in Table 8.7.

$$\tilde{R} = \left[\tilde{r}_{ij}\right]_{m\times n}, \quad i = 1, 2. . . m; \;\; j = 1, 2, . . . , n \tag{8.9}$$

where: $\tilde{r}_{ij} = \left(\frac{a_{ij}}{c_j^*}, \;\; \frac{b_{ij}}{c_j^*}, \;\; \frac{c_{ij}}{c_j^*}\right)$ and $c_j^* = \max_i \{c_{ij}\}$

Step v: Compute the weighted normalized matrix

The weighted normalized matrix $\tilde{V}$ for criteria is computed by multiplying the normalized fuzzy decision matrix $\tilde{r}_{ij}$ by the weights $\tilde{w}_j$ of evaluation criteria using equation 8.10. The weights of criteria have been already calculated in step 8.3.4. The weighted normalized matrix is shown in Table 8.8.

$$\tilde{V} = \left[\tilde{v}_{ij}\right]_{m\times n}, i = 1,2........m; \, j = 1,2......n \tag{8.10}$$

where $\tilde{v}_{ij} = \tilde{r}_{ij}(\cdot)\tilde{w}_j$

Table 8.7 Normalized fuzzy ratings for the alternatives

	C1	**C2**	**C3**	**C4**	**C5**	**C6**	**C7**	**C8**
A1	(0.14, 0.21,0.71)	(0.11 0.22,0.56)	(0.14, 0.29, 1)	(0.56, 0.94,1)	(0.11, 0.50,1)	(0.11,0.44,0.78)	(0.11,0.22, 0.78)	(0.56, 0.94,1)
A2	(0.14,0.36,0.71)	(0.11 0.28,0.56)	(0.14,0.36, 1)	(0.56, 0.89,1)	(0.33, 0.72, 1)	(0.11, 0.5, 1)	(0.11,0.33, 0.78)	(0.33,0.78,1)
A3	(0.14,0.43,1)	(0.11,0.39,0.78)	(0.14,0.43,1)	(0.33, 0.72,1)	(0.11, 0.5, 1)	(0.11, 0.56, 1)	(0.11,0.44, 0.78)	(0.56, 0.78,1)
A4	(0.14, 0.50,1)	(0.33,0.72, 1)	(0.14,0.5,1)	(0.33, 0.67,1)	(0.11, 0.44, 0.78)	(0.11, 0.67,1)	(0.33,0.67, 1)	(0.33, 0.67,1)
A5	(0.14, 0.57,1)	(0.33,0.78, 1)	(0.14,0.57,1)	(0.11,0.33,0.78)	(0.11, 0.28, 0.56)	(0.11,0.67,1)	(0.33,0.78, 1)	(0.11,0.5, 1)
c_j^*	7	9	7	9	9	9	9	9

Table 8.8 Weighted normalized alternatives

	C1	**C2**	**C3**	**C4**	**C5**	**C6**	**C7**	**C8**
A1	(0.01,0.01,0.04)	(0.01,0.03,0.07)	(0.02,0.03,0.12)	(0.09,0.15,0.15)	(0.02,0.08,0.16)	(0.02,0.07,0.12)	(0.01,0.02,0.07)	(0.07,0.13,0.13)
A2	(0.01,0.02,0.04)	(0.01,0.04,0.07)	(0.02,0.04,0.12)	(0.09,0.14,0.15)	(0.05,0.11,0.16)	(0.02,0.08,0.16)	(0.01,0.03,0.07)	(0.04,0.10,0.13)
A3	(0.01,0.02,0.05)	(0.01,0.05,0.1)	(0.02,0.05,0.12)	(0.05,0.11,0.15)	(0.02,0.08,0.16)	(0.02,0.09,0.16)	(0.01,0.04,0.07)	(0.07,0.10,0.13)
A4	(0.01,0.03,0.05)	(0.04,0.09,0.13)	(0.02,0.06,0.12)	(0.05,0.10,0.15)	(0.02,0.07,0.12)	(0.02,0.11,0.16)	(0.03,0.06,0.09)	(0.04,0.09,0.13)
A5	(0.01,0.03,0.05)	(0.04,0.10,0.13)	(0.02,0.07,0.12)	(0.02,0.05,0.12)	(0.02,0.04,0.09)	(0.02,0.11,0.16)	(0.03,0.07,0.09)	(0.01,0.07,0.13)
FPIS	0.05	0.13	0.12	0.15	0.16	0.16	0.09	0.13
FNIS	0.01	0.01	0.02	0.02	0.02	0.02	0.01	0.01

Table 8.9 Distance of alternatives from FPIS and FNIS

	d_v(A1,A^*)	**d_v(A2,A^*)**	**d_v(A3,A^*)**	**d_v(A4,A^*)**	**d_v(A5,A^*)**	**d_v(A1,A^-)**	**d_v(A2,A^-)**	**d_v(A3,A^-)**	**d_v(A4,A^-)**	**d_v(A5,A^-)**
C1	0.04	0.03	0.03	0.03	0.03	0.02	0.02	0.03	0.03	0.03
C2	0.10	0.09	0.08	0.05	0.05	0.03	0.04	0.05	0.08	0.09
C3	0.08	0.08	0.07	0.07	0.07	0.06	0.06	0.06	0.07	0.07
C4	0.04	0.04	0.06	0.07	0.10	0.12	0.11	0.10	0.10	0.06
C5	0.09	0.07	0.09	0.10	0.11	0.09	0.10	0.09	0.07	0.04
C6	0.10	0.09	0.09	0.09	0.09	0.07	0.09	0.09	0.10	0.10
C7	0.06	0.06	0.06	0.04	0.04	0.04	0.04	0.04	0.06	0.06
C8	0.03	0.05	0.04	0.06	0.08	0.10	0.09	0.09	0.08	0.08

Step vi: Compute the Fuzzy Positive Ideal Solution (FPIS) and the Fuzzy Negative Ideal Solution (FNIS)

The FPIS and FNIS of the alternatives are computed using equation 8.11 and 8.12 respectively

$$A^* = (\tilde{v}_1^* \quad \tilde{v}_2^* \quad .... \quad .... \quad \tilde{v}_n^*)\text{, where } \tilde{v}_j^* = \max_i \{v_{ij}\}, i = 1,2,......m; j = 1,2......n \qquad (8.11)$$

$$A^- = (\tilde{v}_1^- \quad \tilde{v}_2^- \quad .... \quad .... \quad \tilde{v}_n^-)\text{, where } \tilde{v}_j^- = \min_i \{v_{ij}\}, i = 1,2,......m; j = 1,2......n \qquad (8.12)$$

Step vii: Compute the distance of each alternative from FPIS and FNIS

The distance of each weighted alternative ($\tilde{v}_{ij}$) from FPIS ($\tilde{v}_j^*$) and FNIS ($\tilde{v}_j^-$) is given by $d_v(\tilde{v}_{ij,}\tilde{v}_j^*)$ and $d_v(\tilde{v}_{ij,}\tilde{v}_j^-)$ and is shown in Table 8.9. This distance is calculated by vertex method i.e. if $\tilde{a} = (a_1, a_2, a_3)$, and $\tilde{b} = (b_1, b_2, b_3)$ are two triangular fuzzy numbers, then the vertex distance is given by equation 8.13.

$$d(a,b) = \sqrt{\frac{[(a_1 - b_1)^2 + (a_2 - b_2)^2 + (a_3 - b_3)^2]}{3}} \qquad (8.13)$$

Step viii: Compute the closeness coefficient (CCij) and aggregate closeness coefficient (Ci) of each alternative

The closeness coefficient CC_{ij} represents the distances to the fuzzy positive ideal solution (A^*) and the fuzzy negative ideal solution (A^-) simultaneously. Closeness coefficient of alternatives with respect to each criterion is calculated by equation 8.14 and shown in Table 8.10.

$$CC_{ij} = \frac{d_v(A_i, A^-)}{d_v(A_i, A^-) + d_v(A_i, A^*)} \qquad (8.14)$$

for each i= 1,2….m and j = 1,2…..n

The aggregate closeness coefficient of each alternative is calculated as

$$CC_i = d_i^- /(d_i^- + d_i^*), i = 1,2.......m$$

Where (d_i^*, d_i^-) is the distance of each weighted alternative i = 1, 2. . . m from the FPIS and the FNIS and is computed as follows:

$$d_i^* = \Sigma_{j=1}^n d_v(\tilde{v}_{ij,} \tilde{v}_j^*), i = 1,2......m$$

$$d_i^- = \Sigma_{j=1}^n d_v(\tilde{v}_{ij,} \tilde{v}_j^-), i = 1,2......m$$

Where $d_v(\tilde{v}_{ij,} \tilde{v}_j^*)$ and $d_v(\tilde{v}_{ij,} \tilde{v}_j^-)$ is the distance measurement of $\tilde{v}_j^*$ and $\tilde{v}_j^-$ from $\tilde{v}_{ij}$.

The aggregate closeness coefficient (CC_i) and distance of each alternative from FPIS and FNIS is shown in Table 8.11. The closeness coefficient of alternatives with respect to each criterion and the aggregate closeness coefficient are shown in Figure 8.2 for easy comparison.

Table 8.10 Closeness coefficient for alternatives with respect to each criterion

CC_{ij}	A1	A2	A3	A4	A5
Initial Investment	0.3248	0.355	0.4673	0.4834	0.5
Labour Cost	0.2663	0.2787	0.396	0.604	0.6172
Energy Consumption	0.4378	0.4519	0.4673	0.4834	0.5
Material Recovery	0.7433	0.7337	0.604	0.5898	0.3828
Environmental Impact	0.4875	0.604	0.4875	0.4102	0.2787
Health & Safety	0.4102	0.4875	0.5	0.5248	0.5248
Processing Time	0.3599	0.3828	0.4102	0.5898	0.6172
Degree of Flexibility	0.7433	0.6172	0.7066	0.5898	0.4875

Table 8.11 Aggregate closeness coefficient for alternatives

	A1	A2	A3	A4	A5
d_i^*	0.538	0.5151	0.5291	0.5016	0.5646
d_i^-	0.52093	0.5423	0.5544	0.5749	0.5183
CC_i	0.492	0.5129	0.5117	0.5341	0.4786

Step ix: Rank the alternatives

The alternatives are ranked according to the closeness coefficient (CC_i) in decreasing order and the alternative with the highest closeness coefficient is selected for final implementation. The best alternative is closest to the FPIS and farthest from the FNIS. Figure 8.3 represents the closeness coefficient of alternative LiB recycling processes with respect to each and aggregate criteria. The final ranking of alternatives under the decreasing order of CC_i and is shown in Table 8.12.

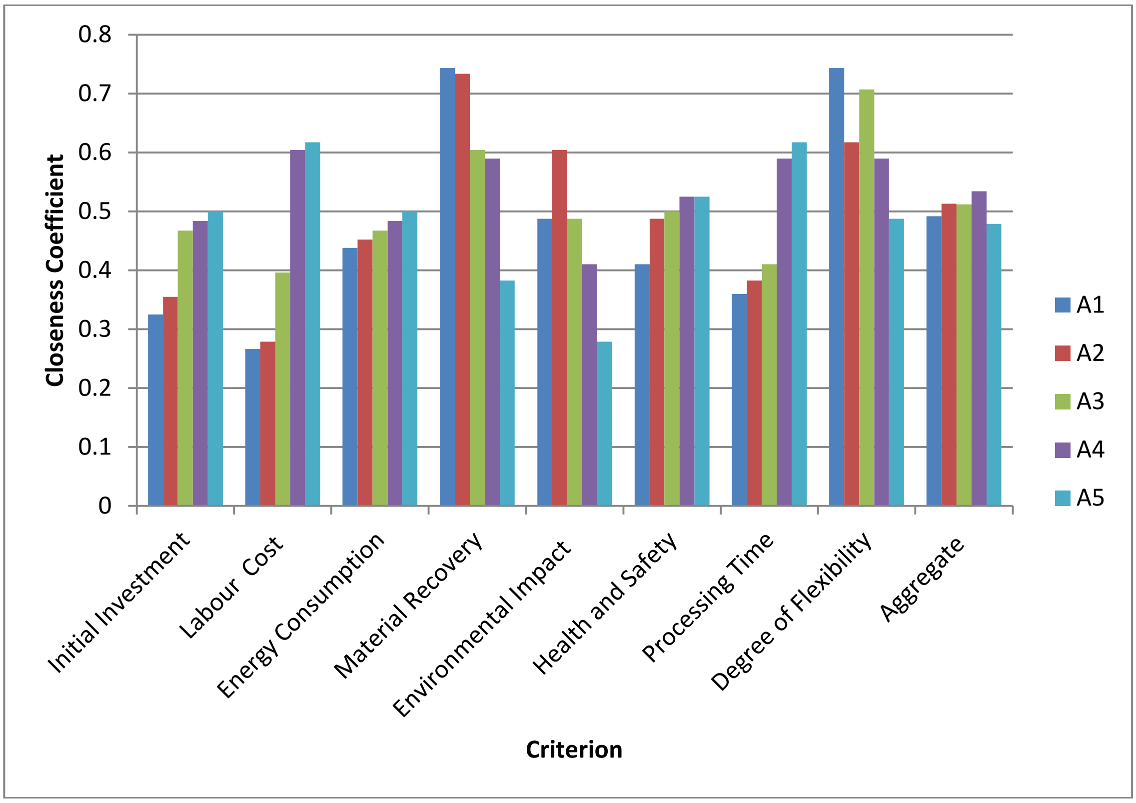

Figure 8.3 Closeness coefficient and aggregate closeness coefficient of alternatives

Table 8.12 Ranking of LiB recycling processes

Alternative LiB Recycling Processes	**Rank**
Pyrometallurgy-hydrometallurgy combination (A4)	1st
Disassembly-mechanical conditioning-hydrometallurgy combination (A2)	2nd
Disassembly-pyrometallurgy-hydrometallurgy combination (A3)	3rd
Disassembly-mechanical conditioning-pyrometallurgy-hydrometallurgy combination (A1)	4th
Pyrometallurgy (A5)	5th

8.4. Results and Discussion

The computed weights for the eight criteria to evaluate the various recycling alternatives using fuzzy AHP method are 0.159 (health & safety), 0.156 (environmental impact), 0.155 (material recovery), 0.134 (degree of flexibility), 0.131 (labor cost), 0.122 (energy consumption), 0.09 (processing time), and 0.052 (initial investment). It shows that under the given circumstances, the four experts perceive health & safety aspects of the recycling process (weight 0.159) as the most important criterion to select the different recycling alternatives for LiB batteries. This is closely followed by the environmental impact (weight 0.156) of the process and the amount of material recovered (weight 0.155) by the process. The initial investment required for the recycling process is given the least importance (weight 0.052). The recycling time is also given a low importance (weight 0.09).

It can be observed from Table 8.10, Table 8.11 and Figure 8.3 that the best alternative under the given circumstances is combination of pyrometallurgy and hydrometallurgy. However, it is interesting to note that this combination is not single best on any individual criterion, it shares the best position with alternative A5 (pyrometallurgy) for health & safety criterion. This is because this combination performs consistently well on most of the criteria. Alternative A5 (Pyrometallurgy) is best recycling process if users consider initial investment, labour cost, energy consumption and processing time criteria. However, pyrometallurgical conditioning provides poor material recovery as some of the recoverable materials get burnt. The burning of materials also leads to high environmental impact. The degree of flexibility is also less in pyrometallurgical conditioning. Alternative A1 (disassembly, mechanical conditioning, pyrometallurgical, and hydrometallurgical conditioning combination) provides the highest material recovery and degree of flexibility as all materials are separated out and recovered by different processes. Alternative A2 (disassembly, mechanical conditioning and hydrometallurgical conditioning combination) is best recycling chain as far as environmental impact is concerned. This is because it does not include the pyrometallurgical conditioning in which parts likes casing and electronics are burned, releasing high effluents to the environment. Pyrometallurgical conditioning alone (alternative A5) is a quick and cost effective recycling process. It ranks best for five criteria but because of very poor ranking/score for environmental impact and material recovery makes this process least ranked under the given circumstances. It will be interesting to find how this process will be ranked by the users/experts from developing countries where the cost will be a dominating factor. Therefore, the results obtained in this study cannot be standardized as these depend on the knowledge, experience, and input of the decision makers. As this case study has been done with the help of only German experts, one of its consequences is that the high weights are obtained for environmental impact, and health & safety criteria. However, for developing and emerging countries, the initial investment may be more important resulting in different ranking. The objective of this study is to provide a robust process for evaluation of different LiB battery recycling processes and not the final result.

CHAPTER 9

CONCLUSIONS AND FUTURE SCOPE

In this chapter, a summary of the research and major conclusions are presented. The objectives of the thesis are: (i) to design and optimize a generalized closed-loop supply chain for single-objective and multi-objective optimization considering the uncertainty in parameters, (ii) to develop multi-criteria decision models for the assessment and evaluation of collection methods, product recovery processes and network configuration in reverse logistics.

In Chapter 2, the definitions and scope of reverse logistics and closed-loop supply chain have been reviewed. From the different definitions of reverse logistics given by different researchers, it has been observed that the scope of reverse logistics is widening with time, starting with a sense of reverse movement, then going through product recovery and finally considering the environmental and social factors of sustainability. It has also been observed that different authors have used different terminologies to refer to the same concepts or the same terminologies to different concepts in the area of reverse supply chain management.

Further with the literature review and close examination of the existing reverse logistics models it was observed that most of the models are either specific to a product or an industry type and different models considered different set of product recovery options, different set of reverse logistic cost, different set of binary variables, different set of uncertain variables and different methods to the handle uncertainty in parameters. So, it is recognized to design and optimize a multi-product, multi-time, multi-echelon capacitated closed-loop supply chain that considers the different costs (i.e. incentive to customer, processing and set-up cost at facility centers, transportation cost, profit from recycling and waste disposal cost), different product recovery options (i.e. reuse, recycle, remanufacture and disposal), and uncertainty in parameters (i.e. demand of product; unit cost of collection, disassembly, refurbishing and disposal; set-up cost at each facility center; capacity of each facility center; unit purchasing cost and maximum percentage of parts that can be reused, refurbished recycled and disposed) simultaneously in the model.

Chapter 3 presented a multi-product, multi-echelon capacitated closed-loop supply chain network and single objective optimization model in an uncertain environment for single-time period returns, which is further extended to multi-time period returns with inventory flow. The uncertainty related to ill-known parameters (i.e. product demand, percentage of return, transportation cost, processing and set up cost, and percentage of parts recovered for reuse, disassemble, refurbish, disposal and recycle) has been handled with triangular fuzzy numbers. A fuzzy mixed-integer linear programming model has been developed to represent the proposed network in mathematical terms to maximize the profit of organization by optimally deciding the quantity of parts to be processed at each reverse supply chain facility and the number of parts to be purchased from multiple suppliers. It has also provided optimal allocation to different collection centers, disassembly centers, refurbishing centers and external suppliers. The model has also considered the product acquisition cost, transportation cost, collection and inspection cost, disassembly cost, refurbishing cost, disposal cost, set-up cost, and recycling profit at various facility locations. The proposed solution methodology has been able to provide a balanced solution between the feasibility degree and degree of satisfaction of the decision maker. The proposed model has been tested with an illustrative example using LINGO 13.0.

Chapter 4 presented the design and optimization of a multi-objective closed-loop supply chain considering the economical and environmental factors with uncertainty in parameters. The two objectives functions considered in the model are: (i) maximizing the profit of the organization and (ii) minimizing the carbon footprints of the transportation in reverse supply chain. The proposed network is modeled as fuzzy multi-objective mixed integer linear programming problem considering multi-customer zones, multi-collection centers, multi-disassembly centers, multi-refurbishing centers, multi-external suppliers, and different product recovery processes to take care of purchasing cost, transportation cost, processing cost, set-up cost, and capacity constraints simultaneously. The model has been solved using an interactive ε-constraint method. A case example has been solved using LINGO 14.0 to demonstrate the significance and applicability of the developed fuzzy optimization model as well as the usefulness of the proposed solution approach.

In Chapter 5 an integrated fuzzy multi-criteria decision model has been provided for the assessment and evaluation of different collection methods. The assessment has been done based on the criteria of initial investment, value added recovery, return volume, operating cost, degree of supply chain control, and level of customer satisfaction. The three alternatives selected in the study are collection directly by the original equipment manufacturer from the customer, collection by the retailer and collection by the third party logistics providers. Fuzzy analytical hierarchy process (Fuzzy AHP) has been used to compute the criteria weights and fuzzy technique for order preference by similarity to ideal solution (Fuzzy TOPSIS) has been used to rank the alternative collection methods. This provided a proper tool to encounter the uncertain and complex environments by measuring the inherent ambiguity of decision maker’s subjective judgment. The proposed model will help companies in strategic decision making to prioritize and develop collection facilities accordingly.

The utility of the proposed evaluation methodology has been validated by solving a case example from Indian automotive sector. Under the given circumstances, the study has concluded that value added recovery has highest weight (0.393) followed by degree of supply chain control (0.26), customer satisfaction (0.16), operating cost (0.09), initial investment (0.06) and return volume (0.04). It demonstrates that the auto manufacturers in India give more weightage to the value added recovery and supply chain control as manufacturers do not want their propriety parts to reach into grey market. From the ranking of alternative collection methods it has been observed that collection directly by the original equipment manufacturer is the best method as it provides the highest value added recovery, highest degree of supply chain control and best customer satisfaction. It is followed by collection by the retailers and collection by third party logistics provider.

Chapter 6 presented an integrated fuzzy multi-criteria decision model for the assessment and evaluation of different product recovery processes. The assessment has been performed based on the criteria of operating cost, value added recovery, environmental impact, market demand, technical/operational feasibility, and corporate social responsibility. The five alternative product recovery processes identified are repair, refurbishing, remanufacturing, cannibalizing, and recycling.

The utility of the proposed methodology is validated through a case example from Indian electronic sector. Under the given circumstances, the study has observed that operating cost has the highest weight (0.323) followed by value added recovery (0.262), market demand (0.208), technical/operational feasibility (0.129), environmental impact (0.046), and corporate social sustainability (0.032). This demonstrated that the electronic manufacturers are interested in reverse supply chain management to save operating costs, recover maximum value and fulfill the market demand rather than the environmental impact and corporate social sustainability. The ranking of alternative product recovery processes has been done based on individual and aggregate criteria. With respect to operating cost repair is best recovery process followed by recycling, as they require least initial investment and degree of disassembly thus reducing the operating cost. In terms of environmental impact (i.e. resource consumption, resource conservation and waste generated) repair and refurbishing are the best recovery alternatives closely followed by remanufacturing as they consume less resources and generate less waste as compared to the other recovery alternatives. Whereas recycling and cannibalization are the least preferred alternatives as these processes require additional energy to convert the product into useful material and waste generation is also high. With respect to market demand refurbished and remanufactured products are most preferred as these processes provide the desired reliability and quality standards. Remanufacturing provides reliability as high as of new product if not more. However, remanufacturing requires each part to be disassembled, therefore a high degree of work content is involved. Therefore the technical/operational feasibility of the process is low. But because of high work content, the number of job opportunities increases in remanufacturing and therefore it is most preferred in terms of corporate social responsibility followed by repair. Further with respect to value added recovery repair is the best followed by refurbishing, and recycle is least preferred. In recycling, all the value added during manufacturing is lost and only material value is recovered. Therefore with respect to aggregate of all the criteria’s repair is the best product recovery alternative followed by refurbishing, remanufacturing, recycling, and cannibalizing under the given circumstances.

Chapter 7 presented an integrated fuzzy multi-criteria decision model for the assessment and evaluation of alternative network configurations in reverse logistics. Literature suggested eight network configurations in reverse logistics based on the trade-offs at collection stage, sorting/testing stage and processing stage of products. These network configurations are assessed and evaluated based on the economical, environmental and social criteria and their sub-criteria. Collection and transportation cost, sorting and testing cost, processing cost and value added recovery are the sub-criteria considered under economical criteria. Energy use, effluents or waste generated and percentage of product reclaimed are the sub-criteria considered under environmental criteria. Corporate citizenship and social responsibility, improved customer service, and intellectual and propriety information are the sub-criteria considered under social criteria.

The utility of the proposed evaluation methodology has been validated by a case example from Indian automotive sector. Under the given circumstances, the study has observed that economical criterion has highest weight (0.626) followed by social criteria (0.266) and environmental criteria (0.107). Further, out of the four sub criteria under economical criterion, value added recovery is having the highest weight. Similarly, the percentage of product reclaimed and improved customer service is having the highest weights under environmental and social criteria respectively. It shows that in India social and environmental aspects are also taken into consideration but the most important are economical aspects. It has been observed that alternative ‘company specific collection, centralized sort/test, and original facility processing’ is the best network configuration under the economical and environmental criteria. But alternative ‘company specific collection, distributed sort/test, and original facility processing’ is the best network configuration under the social criteria. Considering the aggregate effect of all the criteria, ‘company specific collection, centralized sort/test, and original facility processing’ is the best alternative followed by company specific collection, distributed sort/test, and original facility processing, for Indian automobile reverse logistics network.

Chapter 8 presented a case study carried out in Germany, for the assessment and evaluation of recycling processes for lithium-ion batteries (LiBs) from electric vehicles. The increasing environmental degradation, fossil fuel prices, and political implications of fossil fuel dependency on few countries have increased the demand of electric vehicles with lithium-ion batteries. However, the increasing demand of lithium-ion batteries has also increased the demand for its recycling due to scare natural resources like cobalt and lithium required for its manufacturing.

In general, different combination of disassembly, mechanical conditioning, pyrometallurgy, and hydrometallurgy are used in to recover the main components from spent LiBs. The possible alternative combinations selected for this study are: A1 (disassembly-mechanical conditioning-pyrometallurgy-hydrometallurgy combination), A2 (disassembly-mechanical conditioning-hydrometallurgy combination), A3 (disassembly-pyrometallurgy-hydrometallurgy combination), A4 (pyrometallurgy-hydrometallurgy combination), and A5 (pyrometallurgy). To evaluate these alternative process combinations a fuzzy multi-criteria decision model has been developed. Energy consumption, material recovery, environmental impact, health & safety, processing time, degree of flexibility initial investment and labor cost have been selected as the evaluation criteria from literature review and discussion held with four LiB recycling expertsin Germany.

The study showed that under the given circumstances, the four experts perceived health & safety aspects of the recycling process (weight 0.159) as the most important criterion to select the different recycling alternatives for LiB batteries. This is closely followed by the environmental impact (weight 0.156) of the process and the amount of material recovered (weight 0.155) by the process. The initial investment required for the recycling process is given the least importance (weight 0.052). This is probably because of the EU directives that consider health, safety and environment as the most important for any organization.

After calculating the criteria weight, the alternative recycling process combinations have been evaluated with respected to individual and aggregate criteria. Alternative A1 (disassembly-mechanical conditioning-pyrometallurgy-hydrometallurgy combination) provides the highest material recovery and degree of flexibility in terms of size and shape of the battery. Therefore alternative A1 is the best alternative process with respect to these criteria. With respect to environmental impact alterative A2 (disassembly-mechanical conditioning-hydrometallurgy combination) is best process. Whereas with respect to health and safety alternative A4 (pyrometallurgy-hydrometallurgy combination) and A5 (pyrometallurgy) share the best alternative process. Pyrometallurgical conditioning alone (A5) is a quick and cost effective recycling process. It is coming as the best alternative under the criteria of initial investment, labor cost, energy consumption and processing time, as it can easily be combined with the production of steel or other ferromanganese alloys. It ranks best for five criteria but because of poor ranking with respect to environmental impact and material recovery, this process is least ranked under the given circumstances. By considering the entire criteria together alternative A4 (pyrometallurgy-hydrometallurgy combination) is best recycling process followed by A2 (disassembly-mechanical conditioning-hydrometallurgy combination), A3 (disassembly-pyrometallurgy-hydrometallurgy combination), A1 (disassembly-mechanical conditioning-pyrometallurgy-hydrometallurgy combination) and A5 (pyrometallurgy). It will be interesting to find how these processes will be ranked by the users/experts from developing countries where the cost will be a dominating factor.

Specific Research Contributions of the Thesis

Some of the specific research contributions of the research work are:

- Classification and review of reverse logistics network models based on type of framework, number of objectives, product recovery options, different costs, binary decision variables, and methods of handling uncertainty.
- Development of multi-product, multi-echelon capacitated CLSC for single time period return, which is further extended to multi-time period return with inventory flow.
- Optimization of the single objective CLSC with Fuzzy MILP model.
- Optimization of multi-objective CLSC considering economical and environmental factor using ε-constraint method.
- Development of an integrated fuzzy multi-criteria decision models for the assessment and evaluation of collection methods, product recovery processes and network configuration in reverse logistics.
- A case study for the assessment and evaluation of recycling processes for lithium-ion batteries from electric vehicles.

Limitations and Future Scope of Research

Some of the specific research limitations and future scope of research are:

- The study has proposed the design and optimization of a closed-loop supply chain (CLSC) with Fuzzy MILP model. However, in MILP with the increase in size of problem the computational effort increases exponentially. Therefore some efficient heuristics needs to be developed.

- In multi-objective optimization of CLSC the environmental impact has been measured in terms of carbon footprints of reverse transportation only. However, it will be valuable to consider other sources of environmental impact like reduction of waste, carbon footprints of recovery processes, etc.
- The limitation of the fuzzy multi-criteria decision models is that the results are highly dependent on the input of the decision makers, so the results cannot be standardized. However it will be interesting to compare the results from different industry sectors.
- In this dissertation, fuzzy sets theory has been utilized to handle uncertainty in parameters. However, it will be useful to compare the results with other methods of handling uncertainty such as robust optimization.

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Appendix A

Peer-Reviewed International Journals Publications (Published or Accepted):

[1] **Jindal, A**. and Sangwan, K. S. (2014). "Closed loop supply chain network design and optimisation using fuzzy mixed integer linear programming model." ***International Journal of Production Research***, Vol. 52, No 14, pp. 4156-4173.
ISSN: 0020-7543 (Print), 1366-588X (Online)
*Publisher by **Taylor &Francis**, [SCI Indexed, Impact Factor - 1.46]*

[2] **Jindal, A.** and Sangwan, K. S. 2015. "Network design and optimization for multi-product, multi-time, multi-echelon closed-loop supply chain under uncertainty." ***Procedia – CIRP***, Vol. 29, pp. 656-661.
*Publisher by **ScienceDirect***, ISSN: 2212-8271 *[Scopus Indexed]*

[3] **Jindal, A**. and Sangwan, K. S. (2015). "Evaluation of collection methods in reverse logistics by using fuzzy mathematics." ***Benchmarking: An International Journal***, Vol. 22, No 3.
*Publisher by **Emerald***, ISSN: 1463-5771 *[Scopus Indexed]*

[4] **Jindal, A.** and Sangwan, K. S. (2013). "Development of an Interpretive Structural Model of Drivers for Reverse Logistics Implementation in Indian Industry," ***International Journal of Business Performance and Supply Chain Modelling***, Vol. 5, No. 4, pp.352-342.
*Publisher by **Inderscience***, ISSN: 1758-9401 (Print), 1758-941X (Online)

[5] Sangwan, K. S. and **Jindal, A.** (2012). "An integrated fuzzy multi-criteria evaluation of lithium-ion battery recycling processes," ***International Journal of Sustainable Engineering***, Vol. 6, No. 4, pp.359-371.
*Publisher by **Taylor &Francis***, ISSN: 1939-7038, 1939-7046 *[Scopus Indexed]*

[6] Jindal**, A**. and Sangwan, K. S. (2015). “A fuzzy based decision support framework for product recovery process selection in reverse logistics", ***International Journal of Services and Operations Management. [accepted]***

Peer-Reviewed International Journals Publications (Communicated):

[1] **Jindal, A**. and Sangwan, K. S. (2014). “Multi-Objective Closed-loop Supply Chain Network Design and Optimization using Fuzzy Mathematical Programming." ***Annals of Operations Research***, Manuscript ID: **ANOR-D-14-00567**.

Appendix A

Peer-Reviewed International Conference Publications (Abroad):

[1] **Jindal, A.** and Sangwan, K. S., 2011. "Development of an Interpretive Structural Model of barriers to reverse logistics implementation in Indian industry." *In:* Hesselbach, J. and Herrmann, C. eds. *Glocalized Solutions for Sustainability in Manufacturing*, pp. 448-453. Publisher: **Springer Berlin Heidelberg**; Print ISBN: 978-3-642-19691-1; Online ISBN: 978-3-642-19692-8

Peer-Reviewed International Conference Publications (India):

[1] **Jindal, A**. and Sangwan, K. S. (2013). "An integrated fuzzy multi-criteria evaluation of sustainable reverse logistics network models." ***IEEE International Conference on Fuzzy System****,* Hyderabad, ***D.O.I. - 10.1109/FUZZ-IEEE.2013.6622469***; ISSN: 978-4799-20-6 (Print), 1098-7584 (Online)

[2] **Jindal, A.** and Sangwan, K. S. (2012). "Fuzzy Multi Criteria Evaluation of Collection Methods in Reverse logistics." *In:* Shankar, R., Kumar, A. and Chadhuri, A. eds. ***XVI Annual International Conference of the Society of Operations Management. IIT Delhi***, 296-307.

[3] **Jindal, A.** and Sangwan, K. S. (2012). "Fuzzy Multi Criteria Evaluation of Product Recovery Process." *In:* Bhattacharyya, B., Chakraborty, S. and Doloi, B. eds. ***25th All India Manufacturing Technology, Design and Research Conference (AIMTDR)***. Jadavpur University, Kolkata, 1259-1265. [***ISBN: 978-93-82062-92-9***]

[4] **Jindal, A.** and Sangwan, K. S. (2011). "Fuzzy TOPSIS Method for Lithium Ion Battery Recycling Process Selection." *In:* Sangwan, K. S., Digalwar, A. K. and Sharma, M. eds. ***International Conference on Sustainable Manufacturing: Issues, Trends and Practices***. India: Excellent Publishing House, 266-272. [***ISBN: 978-93-81583-10-4***]

[5] Sharma, S. K. and **Jindal, A.** (2011). "Green Supply Chain Management." *In:* Sangwan, K. S., Digalwar, A. K. and Sharma, M. eds. *International Conference on Sustainable Manufacturing: Issues, Trends and Practices.* Pilani- India: Excellent Publishing House, 255-260. [***ISBN: 978-93-81583-10-4***]

APPENDIX B

About the candidate (Anil Jindal)

Anil Jindal is a Lecturer in the Department of Mechanical Engineering at Birla Institute of Technology and Science, Pilani, Rajasthan, INDIA. He is a graduate in the discipline of Mechanical Engineering from Punjab Technical University, Jalandhar, INDIA in 2003, post-graduate in mechanical engineering with specialization in Rotodynamic Machines from Panjab University, Chandigarh, INDIA in 2005 and pursuing his PhD in closed-loop supply chain network design and optimization from BITS Pilani, INDIA. His teaching and research interests are primarily in the field of industrial engineering and operations research along with analysis of problems using mixed-integer linear programming, multi-objective optimization, fuzzy sets, multi-criteria decision modelling, etc. He is engaged in teaching with various institutes of repute in India from last more than 9 years.

About the supervisor (Prof. Kuldip Singh Sangwan)

Prof. Kuldip Singh Sangwan is Professor in the Department of Mechanical Engineering at Birla Institute of Technology and Science, Pilani, Rajasthan. He did his B.E. and M.E. from Punjab Engineering College, Chandigarh, and PhD from BITS Pilani. He is an active researcher in the field of green manufacturing, reverse logistics, lean manufacturing, sustainable manufacturing, cellular manufacturing systems, and simulation and analysis of machining processes on Titanium alloy. He has guided 6 PhD's and 5 PhD's are in progress in addition to large number of research practices, dissertations, and thesis supervised. He is also an active person in research activities in collaboration with foreign universities like TU Braunschweig, Germany, Mondragon University, Mondragon, Spain, etc. In addition to the teaching and research, he has been on administrative posts like Assistant Dean, Engineering Services Division and Chief, Workshop Unit of BITS Pilani.