CLOSED-LOOP SUPPLY CHAIN OPTIMIZATION UNDER GREENNESS, RELIABILITY, QUALITY, CARBON EMISSIONS AND UNCERTAINTY CONSIDERATIONS

by

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To my family.

TABLE OF CONTENTS

LIST OF TABLES . . . . **vi**

LIST OF FIGURES . . . . **ix**

ABSTRACT . . . . **x**

LIST OF ABBREVIATIONS USED . . . . **xi**

ACKNOWLEDGEMENTS . . . . **xii**

CHAPTER 1 INTRODUCTION **1**

1.1 Balancing economical and environmental growth 1

1.2 Closed loop supply chain and reverse logistics 3

1.3 Research objectives and thesis organization 4

CHAPTER 2 LITERATURE REVIEW **7**

2.1 Introduction 7

2.2 Motivation 8

2.3 Research methodology 9

2.4 Review of literature reviews 10

2.5 Stochastic programming and robust optimization models 14

2.6 Quality and reliability 29

2.7 Carbon emissions 44

2.8 Greenness index 56

2.9 Future research 74

2.10 Conclusion 75

CHAPTER 3 MULTICOMPONENT MULTIPRODUCT CLSC DESIGN WITH TRANSSHIPMENT AND ECONOMIES OF SCALE **76**

3.1 Introduction 76

3.2 Literature review 78
    3.2.1 Economies of scale 78
    3.2.2 Reliability and quality issues 80
    3.2.3 Transshipment issues 83

3.3 Framework of the CSLC network with economies of scale, reliability and transshipment considerations 86

3.4 Model formulation 89

3.5 Numerical examples 94
    3.5.1 Verification phase 94
    3.5.2 Experiment 1 - Investigating the impact of EOS 99
    3.5.3 Experiment 2 - Impact of transshipment 100
    3.5.4 Experiment 3 - Investigating impact of part reliability 103

3.6 Conclusion and future work 105

CHAPTER 4 ROBUST CLSC DESIGN WITH PRE-SORTING AND CARBON EMISSION CONSIDERATIONS 108

4.1 Introduction 108

4.2 Literature review 111
    4.2.1 Sorting 111
    4.2.2 Robust optimization and stochastic programming 114
    4.2.3 Carbon emissions 118

4.3 Framework for CLSC network design with sorting and carbon emission considerations 120

4.4 CLSC design formulation with presorting under the carbon cap or cap and trade policies 123

4.5 Model behaviour 129
    4.5.1 Experiment 1 - Investigating the impact of varying q_{mk} on total emissions and profit 131
    4.5.2 Experiment 2 - Impact of presorting centre inefficiency (β) on opening of presorting centres 132
    4.5.3 Experiment 3 - Impact of increasing transportation cost from Customer Zones (CZs) to the Inspection and refurbishment centre (IRC) (c^1_{mk}) on opening of presorting centres 133
    4.5.4 Experiment 4 - Comparison of carbon cap, cap and trade policies 134
    4.5.5 Experiment 5 - Investigating the effects of C_p on profit as the carbon cap changes 135

4.6 Robust model formulation 136

4.7 Robust model behaviour 142

    4.7.1 Experiment 1 - Investigating impact of varying return quality (q_{mko}) on the network structure, total emissions and profit of the closed-loop supply chain (CLSC) network 143

    4.7.2 Experiment 2 - Impact of varying π on the structure of the CLSC network 144

    4.7.3 Experiment 3 - Impact of increasing C_p on the network profit 145

    4.7.4 Experiment 4 - Comparison between robust and deterministic models 146

4.8 Conclusion and future work 147

CHAPTER 5 CONCLUSIONS 149

5.1 Theme 1: Literature review 149

5.2 Theme 2: Multicomponent multiproduct CLSC design with transshipment and economies of scale 151

5.3 Theme 3: Robust CLSC design with pre-sorting and carbon emission considerations 152

BIBLIOGRAPHY 154

APPENDIX A GLPK codes for MILP models 171

LIST OF TABLES

2.1 Stochastic programming and robust optimization papers summary 16

2.2 Stochastic programming and robust optimization papers summary (continued) 17

2.3 Stochastic programming and robust optimization papers summary (Industry, problems, number of objectives) 18

2.4 Stochastic optmization and robust optimization papers summary (Industry, problems, number of objectives, continued) 19

2.5 Reliability and quality papers summary (1) 30

2.6 Reliability and quality papers summary (2) 33

2.7 Reliability and quality papers summary (3) 37

2.8 Reliability and quality papers summary (4) 40

2.9 Reliability and quality papers final summary (5) 43

2.10 Papers with reliability concepts 43

2.11 Carbon emission based papers summary (carbon cap and carbon tax policy) 46

2.12 Carbon emission based papers summary (carbon cap and trade policy) 50

2.13 Carbon emission based papers summary (absence of carbon policy) 52

2.14 Carbon emission based papers summary 55

2.15 criteria for evaluating supply chains - 1 58

2.16 criteria for evaluating supply chains - 2 59

2.17 criteria for evaluating supply chains - 3 60

2.18 Summary table - criteria for evaluating supply chains 61

2.19 Greenness index - Fuzzy methods focus 62

2.20 Greenness index - Other methods 63

2.21 Summary table for greenness index methods 64

3.1 Summary table for economies of scale (EOS) papers 81

3.2 Summary of papers dealing with quality and reliability issues . 84
3.3 Summary table for transshipment papers 87
3.4 σ_{pm} 95
3.5 Fixed costs and capacities for an Inspection, repair and disassembly centre (IRDC) - without EOS 95
3.6 Fixed costs and capacities for an IRDC - with EOS 95
3.7 Parameters table 96
3.8 Refurbishment, inspection and disassembly costs across all IRDC locations and sizes 96
3.9 Legend for IRDC size 96
3.10 Variation in the type of IRDC opened 96
3.11 IRDC opened with and without Economies of Scale (EOS) . . 100
3.12 C_{ls}^{D} for different scenarios 102

4.1 Summary of papers on Sorting 115
4.2 Summary of papers on Sorting (continued) 116
4.3 Summary of papers on two stage stochastic programming and robust optimization 119
4.4 Summary of papers on carbon emission 121
4.5 Fixed costs and inspection capacities for IRC of different sizes . 129
4.6 Selling price of refurbished product (S_{mk}) 129
4.7 Distance between CZ and IRC, CZ and recycling centre 130
4.8 Product recycling, inspection, refurbishment costs in \$ and product weight in Kg. 130
4.9 Products collected at the CZ (Z_{mk}) 130
4.10 Parameters table 131
4.11 Effect of varying return quality (q_{mko}) on the structure, total emissions and profit of the CLSC network 143
4.12 Return quality scenarios to study effects of varying π on the structure of the CLSC network 144

4.13 Number of presorting centres opened and IRC size for different scenarios 145

4.14 Return quality scenarios used in experiment to study impact of increasing C_p on the network profit 146

4.15 Variation of network profit for increasing C_p (baseline at $C_p = 0.27$) 146

4.16 Comparing results of robust and deterministic model 147

LIST OF FIGURES

3.1 Representation of the Closed-loop supply chain network 88

3.2 Multi component products: assembled from multiple parts . . 94

3.3 Relationship between inspection capacity of an IRDC and its fixed cost of opening 95

3.4 Economical operating range for reverse flow with EOS 97

3.5 Profit as a function of return rate 98

3.6 Profit as a function of return rate for diverse d_{mk}^{R} 99

3.7 Effects of economies of scale on the difference in profit 100

3.8 Effects of varying transshipment cost on the difference in profit 102

3.9 Effects of varying disassembly capacity of IRDC on the difference in profit 103

3.10 Effects of variation of γ_p on profit under different scenarios of d_{mk}^{R} 105

4.1 Representation of the closed-loop supply chain network 122

4.2 Effects of varying q on total emissions and profit 132

4.3 Impact of presorting centre inefficiency (β) on the opening of presorting centres for different q_{mk} 133

4.4 Impact of increasing transportation cost from CZs to IRCs (c_{mk}^{1}) on the opening of presorting centres for different q_{mk} 134

4.5 Emissions and profit for carbon cap policy 135

4.6 Emissions and profit for carbon cap and trade policy 136

4.7 Effects of C_p on profit as the carbon cap changes 137

4.8 Effect of varying return quality (q_{mko}) on the structure, total emissions and profit of the CLSC network 144

ABSTRACT

Organizations achieve economic and environmental benefits through CLSC activities. This thesis contributes to CLSC design through an extensive literature review focussing on: 1) robust and stochastic optimization, 2) product quality and reliability, 3) carbon emissions, and 4) the greenness index. Articles are classified according to several criteria.

Two CLSC mathematical modelling approaches to maximize network profit are proposed based on identified gaps in the literature. The model in the first approach incorporates the effects of EOS and part reliability on IRDCs location in the presence of transshipment of inspected products between IRDCs. In the second approach, a deterministic model with presorting facilities to reduce transportation costs and carbon emissions is developed. A robust optimization extension is proposed to deal with uncertain return product quality. Several numerical experiments are conducted to help understand the behaviour of the formulations and gain managerial insights.

LIST OF ABBREVIATIONS USED

3PL	Third-Party Logistics Provider
AHP	Analytic Hierarchy Process
ANP	Analytical Network Process
BOM	Bill of Materials
CVRP	Capacitated VRP
CZ	Customer Zone
CLSC	Closed-Loop Supply Chain
EOL	End-of-Life
EOS	Economies of Scale
EOU	End-of-Use
GA	Genetic Algorithm
GHGE	Greenhouse Gas Emissions
GSCM	Green Supply Chain Management
GVRP	Green Vehicle Routing Problem
IRC	Inspection and Refurbishment Centre
IRDC	Inspection, Repair and Disassembly Centre
IR	Independent Remanufacturer
JIT	Just-in-Time
LP	Linear Programming
MILP	Mixed-Integer Linear Program
MINLP	Mixed-Integer Non Linear Program
MIP	Mixed-Integer Program
NLP	Nonlinear Programming
OEM	Original Equipment Manufacturer
OR	Operations Research
PC	Personal Computer
RC	Recycling Centre
RL	Reverse Logistics
RO	Robust Optimization
ROHS	Restriction on Hazardous Substances
RTI	Returnable Transport Items
SCM	Supply Chain Management
SRI	Socially Responsible Investing
VRP	Vehicle Routing Problem
WEEE	Waste Electrical and Electronic Equipment

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CHAPTER 1

INTRODUCTION

This thesis by article looks at logistical issues in CLSC design. Such systems have gained popularity both in academia and practice and have begun to make significant impact in industry.

1.1 Balancing economical and environmental growth

“Faster, Higher, Stronger” the Olympics motto is true for business organizations as they are in constant pursuit of increasing their sales and thereby their profits. Due to this incessant urge to be better than their competitors, organizations manufacture products at cheaper rates through mass production. Most often, products in the past were made from virgin material. Due to the vast amounts of raw materials used to satisfy the demand from organizations we now find the level of natural resources reaching dangerously low levels, while at the same time, pollution in all forms (air, land, and water) is at record high levels.

Mass production along with a lack of end-of-life (EOL) legislations to dispose used products led to an increase in the amounts of waste products generated. Plastic is one such product which has grabbed the spot light in recent times. It is one of the most abundant waste products found on the planet. Plastics are strong, durable and cheap, which is a boon to manufacturers; but these characteristics act as a double-edged sword at the end of the products life, as they make disposal difficult. If plastic waste if improperly discarded, it can be a hazard to wild life. Animals and fish ingest this waste unknowingly and it may lead to the death of the species (Laist, 1987; Derraik, 2002)

Carbon emissions have also risen in the last few decades resulting in an increase in global warming. The effects of global warming can be seen quite distinctly. Rising ocean levels, warming of ocean waters, breaking sea ice and glaciers, changes in the amount of precipitation, adverse weather conditions, and other effects. This, in turn affects plants and animal life (Hughes, 2000). As most elements on the earth are interconnected and interdependent we may inadvertently cause our own extinction as the earth turns more into a barren desert due to effects such as global warming.

To avoid permanent and irreversible destruction to the Earth, our home, we find a variety of environmental groups such as World Wildlife Federation, Greenpeace, Natural Resources Defense Council and others raising their voices to reduce the impact of human activities on the environment. After several years of protesting and sloganeering, we now find citizens and governments working towards reducing our impact on the environment.

Some of the most significant agreements undertaken by countries include the Kyoto Protocol and the Paris Agreement. The Kyoto protocol is focused on reducing emissions from developed countries and had set legally binding emission reduction goals, while the Paris Agreement has focused on limiting global warming from 2020 onwards to well below 2°C above pre-industrial levels and pursue efforts to limit it to 1.5°C. Though some countries have taken these agreements seriously, there are still many developing and developed countries which have not abided by these agreements (European Council Website, 2018a,b).

Though some countries may not fully acknowledge the impact of their manufacturing activities on the environment, some sections of the business community have taken responsibility. Socially responsible investing (SRI) is a new investing philosophy being adopted. In SRI, environmental sustainability and corporate social responsibility are given top priority before making an investment in an organization. SRI is also known to generate equal or better benefits than from investing using traditional philosophies. Around of 20% of Canadian investments are held in SRI opportunities and this trend is growing (RBC Global Asset Management Report, 2018; RBC Global Asset Management Website, 2018). This shows that pursuing a sustainable strategy can result in a win-win for businesses, investors, consumers and the environment.

1.2 Closed loop supply chain and reverse logistics

Reverse logistics and CLSC provide organizations a tool to be more sustainable. According to Dowlatshahi (2000) “reverse logistics (RL) is a process in which a manufacturer systematically accepts previously shipped products or parts from the point for consumption for possible recycling, remanufacturing, or disposal”. Likewise, CLSC is defined by Guide Jr and Van Wassenhove (2009) 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”

Organizations are increasingly working towards extracting value from returned products. Few industry examples are as follows:
Dell provides like new and refurbished PCs, servers and other networking items at low prices, with warranties and after-sales service comparable to new products and a 30 day return policy. Some products have never been used by its previous owners and are available in its original packaging with software seals intact. Very often there are only cosmetic blemishes on the remanufactured product which does not interfere with its performance (Dell Website, 2018).

In the cell phone space, Samsung is promoting pre-owned phones. Prior to being certified, these pre-owned phones have under gone a detailed top-down inspection process by the same engineers who build the new products. As the phones are remanufactured to original specifications by Samsungs engineers, provided with a one-year warranty, a brand new charger and other accessories, customers will find it difficult to resist such offers (Samsung Website, 2018).

In the engine remanufacturing space, we find Mercedes-Benz offering remanufactured engines as an economic alternative to new engines. Returned engines are disassembled and parts such as the pistons which are subjected to extreme wear are replaced with new parts. Engines are tested for quality and functionality. Similar to mobiles and computers, the engine is backed by a manufacturers warranty (Mercedes Website, 2018).

As gold is expensive to mine, gold obtained from old electronics or from a tooth filling is of extremely high value. We have pawn shops which are ever willing to purchase minuscule amounts of gold from customers. This returned gold is recycled and added to the forward supply chain.

A wood trim manufacturer found an alternative to discarding the large quantities of saw dust and chips generated in the trimming process. Wood briquettes were developed by drying and compressing the waste sawdust and chips. These briquettes can be used as an alternative to firewood. The company converted the hassle of disposing a waste product into an opportunity by opening a new business division to manufacture wood briquettes from wood waste (ChronicleHerald Website, 2018).

There is a large market even for used clothing. The recycling/donation bins present in upscale retailers collect textiles from shoppers and then sells these items at a discounted rate in secondary markets. Canadian used textile exports topped $160 million in 2016 (CBC Website, 2018).

From the various examples, we can see that there is a lot of value hidden in returned or EOL items. Thus, we find a focus in recent years on CLSC and RL issues resulting in a wide variety of articles being published in the literature.

1.3 Research objectives and thesis organization

CLSC and RL literature can be classified into designing, planning, surveys conducted using questionnaire/interviews, product pricing and coordination, production planning, inventory management, studies focused on a variety of different issues, conceptual and analytical frameworks, review and partial review articles, decision making and performance evaluation, third party reverse logistic providers, vehicle routing problems, etc. (Govindan, Soleimani, and Kannan, 2015).

Though Govindan et al. (2015) surveyed a vast number of CLSC and RL articles from January 2007 to March 2013, we found that there many new articles published since. In this thesis, the focus is on analyzing articles on overcoming uncertainty, articles considering return product quality and reliability, and articles with a carbon emission focus. In particular, we look at research on developing a greenness index to measure the performance of CLSC and RL. Therefore, the first contribution of this thesis is a literature review focussing on these aspects.

Although there is a vast number of CLSC and RL articles as seen in Govindan et al. (2015), it was found that EOS, transshipment and part/product reliability have received relatively lower coverage. The second contribution of this thesis is the network design of a multi-component multi-product CLSC with EOS for IRDCs location, transshipment of inspected products between IRDCs, and return product reliability. The proposed model extends the mixed-integer linear program (MILP) in Venkatadri, Diallo, and Ghayebloo (2017). The behaviour of such a system is characterized using an example.

Since CLSC systems in real life involve significant uncertainties, researchers have started using robust optimization (RO) and stochastic programming methods to design and predict the performance of such systems. However, the literature review indicated a gap in coverage in the sorting of returns when return product quality is uncertain and emissions analysis. The third contribution of the thesis is the development of a robust CLSC design model in which presorting facilities are located to overcome uncertainty in return product quality. Effects of carbon emission policies such as carbon cap and carbon cap and trade on the network are analyzed within the model framework. Using a numerical example, the following aspects are investigated: 1) The effects of varying return quality on total emissions and profit, 2) The impact of presorting centre efficiency and transportation cost on the opening of presorting centres, and 3) A comparison of the impact of carbon cap and cap and trade policies on the configuration of the network.

The rest of the thesis by articles is organized as follows. Chapter 2 contains a literature review through a paper entitled: “Review of reverse logistics and closed loop supply chain with a focus on uncertainty, product quality and reliability, carbon emissions and greenness index.” Chapter 3 details the design of a CLSC model in a paper entitled: “Multicomponent multiproduct CLSC design with transshipment and EOS.” Chapter 4 proposes a robust CLSC in an article entitled: “Robust CLSC design with pre-sorting and carbon emission considerations.” Finally, Chapter 5 presents some concluding remarks on the thesis.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

A closed-loop supply chain is the integration of forward and reverse supply chain processes (Guide Jr and Van Wassenhove, 2009). Activities such as repair, remanufacturing, refurbishing and recycling are included in CLSC management. The recycling industry processes more than 600 million tonnes of recyclables every year, employs close to 1.6 million workers and generates an annual turnover of USD 200 billion worldwide (Bureau of International Recycling Website, 2018). The remanufacturing industry in the United States was valued at USD 43 billion and supported 180,000 full time employment opportunities between the years 2009–2011 (United States International Trade Commission Report, 2018). The revenue and job opportunities generated by recycling and remanufacturing activities alone are sufficient to encourage industry leaders and governments to work towards sustainable manufacturing. Refurbishing, reuse and other CLSC activities generate even more economic opportunities. Monetary benefits which are one of the primary motivators to pursue any business opportunity is thus fulfilled. Consumers are also motivated to support CLSC activities as they assist in protecting the scarce resources of the planet (water, forests, minerals, etc.), help maintain cleaner environment, improve quality of life for present and future generations. CLSC activities derive socio-economic benefits for consumers, industry partners and governments.

Remanufacturing is supported by industry leaders such as Caterpillar for construction equipment, Toyota, Volkswagen and General Motors for automobiles, Apple Inc. for consumer electronics. Toyota, Volkswagen and General Motors sell remanufactured automotive parts to their customers with after-sales service support. According to Volkswagen, remanufactured parts are often sold at half the price of their brand new counterparts. For Volkswagen, their engine remanufacturing program alone has saved them 983 million kW.h of energy, 586,000 tons of CO_2 emissions and enough steel to build 50 Eiffel Towers (Volkswagen Report, 2018). Examples like these are abundant in different sectors of the economy. The potential for profit is so high that Caterpillar conducts remanufacturing for other companies such as Ford (automotive sector) and Honeywell (components) (Caterpillar Website, 2018). Forward logistics organizations such as DHL, UPS, FedEx and others have realized the revenue potential of managing the product return processes and have setup separate divisions for reverse logistics.

Remanufacturing Industries Council and other not for profit organizations are encouraging greater levels of remanufacturing in all sectors of the industry, lobbying for favourable government policies, educating consumers and organizations on the benefits of remanufacturing. People are increasingly recognizing the value of remanufactured products. The International Organization for Standardization (ISO), along with its member organization American National Standards Institute (ANSI), are setting standards for the development of remanufactured goods (For example: ISO 10987–2:2017 for the remanufacturing of earth-moving machinery). Governments have developed and implemented policies for enhanced producer responsibility. The WEEE (Waste Electrical and Electronic Equipment Directive) in use in the European Union and the Electronics Product Stewardship Canada have set standards to guide manufacturers in the recovery and reuse of end-of-use (EOU) or EOL products. Similar regulations have been put forth by other countries.

The ability of CLSC and RL to achieve economical and environmental benefits for organizations has attracted the interest of academia and the research community. As a consequence, there is vast literature dedicated to the investigation of CLSC and RL issues.

2.2 Motivation

The goal of this chapter is to summarize the literature surveyed by Govindan et al. (2015), and complement it by reviewing papers not covered by or published since

Govindan et al. (2015). The CLSC process is strife with uncertainty related to customer demand, product returns, and costs. These uncertainties will prove to be costly in the future if major changes are needed in strategic decisions such as varying the number of manufacturing facilities. A number of articles based on stochastic and robust optimization techniques have been proposed to design CLSC networks that can better handle uncertainty for some key parameters.

Many recently published articles on CLSCs incorporate return product quality, emissions generated and techniques to develop a greenness index. Although there is a vast body of knowledge based on the above mentioned areas, there is a lack of review articles in this area. Hence, the proposed review will be developed to address this shortcoming with the aim of guiding future research.

The rest of the chapter is organized as follows: Section 2.3 contains the research methodology followed in this article. Section 2.4 summarizes existing literature reviews on CLSC and RL. Section 2.5 reviews articles overcoming uncertainty using stochastic programming and robust optimization. Section 2.6 reviews articles on quality and reliability. Section 2.7 reviews articles incorporating carbon emissions in the supply chain. Section 2.8 reviews articles developing greenness indices. Finally, Section 2.9 and 2.10, respectively, shed light on future research opportunities and provides the conclusions.

2.3 Research methodology

Google scholar and Engineering village (Compendex) were the main search engines which provided relevant journal articles, conference papers and related literature. The following keywords were used for the search: Closed loop supply chain, reverse logistics, uncertainty, robust optimization, stochastic programming, quality, reliability, carbon emission, performance measurement/evaluation and green supply chain management. Publishers such as Springer, Taylor and Francis, IEEE, Elsevier and Emerald Group provided relevant articles.

Problem Context: We studied articles on CLSC and RL with a focus on uncertainty, return product quality and reliability, carbon emissions and greenness index.

Methodology: Papers on uncertainty are classified according to the type of uncertainty under consideration and industry application. Articles on return quality and reliability are categorized based on the similarity of settings (number of periods, components and products) and quality attributes (grading and pricing). Carbon emission papers are classified according to the carbon policy followed in the article. Articles on greenness index are classified according to the method used in developing an index to measure the performance of the supply chain.

2.4 Review of literature reviews

A vast literature on CLSC and green supply chain management (GSCM) has emerged in recent years. Hence we have a large number of literature review articles which have analyzed, categorized, drawn conclusions and found future research opportunities. One of the pioneering literature review articles was published by Govindan et al. (2015), who evaluated 382 papers published between January 2007 and March 2013. We have utilized the review/partial review papers in Govindan et al. (2015) and other publications to create a comprehensive summary of existing literature reviews. Some of the noteworthy literature review papers in Govindan et al. (2015) are Sasikumar and Kannan (2009), who reviewed 543 articles across the whole spectrum of reverse supply chain and classified them according to content related issues and solution methodologies adopted by researchers and Ilgin and Gupta (2010), who reviewed 540 articles based on environmentally conscious manufacturing and product recovery, and classified papers on the basis of product design, remanufacturing, disassembly and supply chain strategy.

The literature reviews not covered by Govindan et al. (2015) range from articles targeting a specific research area to articles encompassing the breadth of CLSC and RL.

Review articles with a general focus are reviewed first. Govindan and Soleimani (2016) reviewed and categorized 83 papers on RL and CLSC published in the Journal of Cleaner Production before December 2014. 69 papers were found to lie in the RL category and the remaining 14 belonged to CLSC. Based on the research fields, papers were classified into remanufacturing, waste management, recycling, reuse, recovery, disassembly, recycling and general articles.

Souza (2013) studied 98 articles on CLSC, classified them into strategic, tactical and operational issues and presented his work in the form of a tutorial. The tutorial consists of a base model formulation, its assumptions, key results and possible extensions. Greater emphasis was put on strategic and tactical issues. Strategic issues focus on CLSC network design, use of trade-ins and leasing to source returns, incentive and coordinations among network members, remanufacturing by original equipment manufacturers (OEMs) while tactical issues focus on the quantity, quality and timing of return acquisition and on methods to dispose products (recycling, remanufacturing etc.

Shaharudin and Zailani (2012) reviewed 74 articles on CLSCs and RL with a focus on production and operations management, business logistics and logistics management. From the 74 articles, 10 considered both CLSCs and RL, 17 articles were based only on RL while the rest were based only on CLSC. They found that there is growing interest towards social, economic and environmental protection. They concluded that surveys and exploratory cross-sectional studies could be avenues for future research.

In what follows, we review literature review articles dealing with specific research areas in CLSC/RL.
Bazan, Jaber, and Zanoni (2016) reviewed the literature on the modeling of reverse logistics inventory systems. These inventory systems are based on economic order quantity, economic production quantity and the joint economic lot size. Papers are classified according to the industry problems addressed and modeling assumptions. The authors also focus on the research works conducted by three specific authors: *Schrady, Richter et al., Teunter and El Saadany et al.*

Xu, Zhang, Liu, and Zhao (2012) studied 47 articles on CLSCs and focused on distributed decision making. They found that microeconomics and game theory methods are the primary concepts used in this area. From CLSC optimization point of view, an area which has not been covered extensively is the control and coordination of operations.

Reusable packaging material such as boxes, crates, pallets and trays are used by many industries nowadays. These items are called returnable transport items (RTIs). Glock (2016) reviewed articles that develop decision support models for the management of RTI in CLSCs. 33 papers were categorized into 4 classes: comparison of alternative packaging solutions, forecasting the number and timing of RTIs to be returned, the purchase of new RTIs and management of RTI systems.

Jena and Sarmah (2016) reviewed papers on remanufacturing and paid special attention to acquisition management of returned products. They found that current research is mainly about finding new pricing policies to convince customers to return their used products. They reviewed two books and 100 journal publications between the years 2000 to 2014. They suggested the integration of acquisition management with other related activities such as pricing policy, method of collection and production planning and control as future areas of research.

Stindt and Sahamie (2014) created a synopsis of the literature on CLSC management in the process industry, which is defined as the production of materials rather than the production of items as in the discrete manufacturing industry. They reviewed 66 articles with natural science content and 101 articles with a business perspective. The articles were further classified into surveys, case studies (qualitative and quantitative) and research papers (qualitative and quantitative). Quantitative research papers are classified under network design issues, production planning, product returns management, forecasting. Quantitative case studies are classified according to chemical, construction, metal, paper and pulp and other industries. It was found that research in CLSC management in the process industry is limited and fragmented.

Zhang, Lee, Chan, Choy, and Wu (2015) summarized the literature on the application of swarm intelligence (SI) in green logistics (GL). 115 papers published between the years 1995 to 2014 were reviewed. Green logistics is classified into three sub classes: green performance measurement, green operations implementation and green strategies management.

Schenkel, Caniëls, Krikke, and van der Laan (2015) studied value creation from the recovery of returned products in a CLSC. By reviewing 144 articles between the years 1998 to 2014, from green, reverse and CLSC literature, four types of value manifestations were identified such as economic, environmental, information and customer value. Literature was also classified under the following 6 value adding concepts, namely, partnerships and collaboration, product design, service concepts, IT solutions, supply chain processes and organizational characteristics.

Appolloni, Sun, Jia, and Li (2014) conducted a literature review on green procurement (GP) in the private sector to identify its major themes. 86 papers published between the years 1996 and 2013 were analyzed. Three classification themes are used: 1) Motivation/drivers towards the adoption of green procurement 2) Barriers to the adoption of green procurement 3) Performances of green procurement. A conceptual model for green procurement was developed to help drive future research findings.

Wang (2014) worked on a literature review on GSCM. The paper provides various definitions of GSCM and its developments. The GSCM literature is then classified into green design, green procurement, green manufacturing and remanufacturing, reverse logistics and network design, green recycling and waste management.

Garza-Reyes (2015) reviewed the literature on lean and green initiatives. The author created a concept map and identified six critical research streams based on conceptual and empirical works. The literature is classified according to the following six topics: compatibility between lean and green, integration of lean and green as a consolidated approach, integration of lean-green with other approaches, proposal of a lean-green performance assessment method/indicator, lean-green impact on organizational performance and lean-green research or empirical application.

Lin, Choy, Ho, Chung, and Lam (2014) reviewed the literature on Green Vehicle Routing Problem (GVRP) and found the use of traditional Vehicle Routing Problem (VRP) in GVRP. GVRP is classified into Green-VRP, pollution routing problems and VRP in reverse logistics. Traditional variants of VRP have been summarized under a variety of classes. Papers are categorized based on the types of problem solved rather than the algorithm used.

Diallo, Venkatadri, Khatab, and Bhakthavatchalam (2016) reviewed CLSC literature with a focus on remanufactured/second-hand products and considered quality, reliability, maintenance and warranty issues. 104 articles published after the year 1985 were included in the study. Papers are classified under six categories: Quality models, Reliability models, Maintenance models, Remanufacturing models (disassembly, upgrade, refurbish, reuse), Warranty models, Risk and safety. A secondary classification based on methodology/approach and Mathematical tools & techniques is also presented. They mainly found that the category dealing with risk, safety and hazards models had the fewest number of papers.

This section presented a brief review of literature review papers. The next section is a review of stochastic and robust optimization models in CLSC and RL.

2.5 Stochastic programming and robust optimization models

“The only certainty is that nothing is certain” as quoted by Pliny the Elder, a Roman author, holds true for the situations faced by many organizations today. CLSC and RL networks even feature more uncertainty than the traditional forward supply chains because they deal with input products (cores) that have been used in different ways by customers before being returned. These cores are returned with uncertainty in both quality and quantity. Hence it is beneficial to study uncertainty in these supply chains. Meysam, Maghsud, and Ali (2016) found that most papers working on CLSC are deterministic in nature while the few papers considering uncertain parameters use stochastic programming, and even fewer papers implement fuzzy and robust optimization. Our literature search found the following articles, which are classified based on the uncertainty aspect considered. Tables 2.1 and 2.2 provide a summary of the articles described below.

About 74% of all articles on uncertainty dealt with demand uncertainty. Around 63% of these articles are focused on uncertainty in return quantity. First, we start by reviewing the papers that deal with demand uncertainty.

Wang and Huang (2013) considered demand uncertainty on its own while other authors have considered a combination of demand uncertainty with other uncertainties. In Wang and Huang (2013) a variety of products are disassembled for their components to fulfill uncertain demands in multiple periods. They presented a two-stage robust programming model for demand-driven disassembly/recycling/ remanufacturing planning in a CLSC to determine the right recovery strategy and quantity, and timing for EOL products.

The following papers combine demand uncertainty with other uncertainties Altmann and Bogaschewsky (2014) focused on uncertainty in demand and used product return ratio. They proposed a robust CLSC model with the dual objective of minimizing expected total costs and carbon dioxide equivalents. L_p–metrics method was used to combine both objectives into a single function. The RO method developed by Yu and Li (2000) was employed in this study to create a network which could adapt to varying parameters to the benefit of risk-adverse decision makers.

Cui et al. (2017) designed a CLSC with uncertainty in demand and in quantity of returned products. Genetic Artificial Bee Colony algorithm with a new food source along with crossover and mutation capabilities of genetic algorithm (GA) assisted the model in exploring a greater solution space.

De Rosa et al. (2013) considered uncertainties in the supply and collection of

Table 2.1: Stochastic programming and robust optimization papers summary

Citation	Methods				Robust Methods						Settings						Uncertain Parameters						
	Queueing	MILP	MINLP	Heuristics	Ben-Tal & Nemirovski	Soyster's	Bertsimas and sim	Mulvey / Yu & Li	Other	Stochastic Methods	Single period	Multi period	Single Product	Multi product	Capacitated	Uncapacitated	Demand	Return Quality	Price	Cost	Capacity	Return quantity	Other
Wang and Huang (2013)									*			*		*	*		*						
Altmann and Bogaschewsky (2014)								*				*	*		*		*						used product return ratio
Cui, Guan, Saif, Zhang, Zhang, and Mirza (2017)				*							*		*		*		*					*	
De Rosa, Gebhard, Hartmann, and Wollenweber (2013)		*						*				*	*		*		*					*	
Dubey, Gunasekaran, and Childe (2015)		*			*	*	*					*		*	*		*					*	
Gao and Ryan (2014)					*					*		*	*		*		*					*	carbon emissions
Hasani, Zegordi, and Nikbakhsh (2012)					*							*		*	*		*			*			
Hasani, Zegordi, and Nikbakhsh (2015)			*	*			*					*		*	*		*			*			
Hatefi and Jolai (2014)		*					*		*		*		*		*		*	*				*	
Kara and Onut (2010)								*		*	*		*		*		*					*	
Keyvanshokooh, Ryan, and Kabir (2016)		*					*			*		*	*		*		*			*		*	
Mahmoudzadeh, Sadjadi, and Mansour (2013)							*					*	*		*		*					*	
Meysam et al. (2016)		*			*						*			*	*		*			*			
Mukhopadhyay and Ma (2009)										*	*		*			*	*	*					
Pishvaee, Rabbani, and Torabi (2011)		*			*						*		*		*		*			*		*	

Table 2.2: Stochastic programming and robust optimization papers summary (continued)

Citation	Methods				Robust Methods					Stochastic Methods	Settings						Uncertain Parameters						
	Queueing	MILP	MINLP	Heuristics	Ben-Tal & Nemirovski	Soyster's	Bertsimas and sim	Mulvey / Yu & Li	Other		Single period	Multi period	Single Product	Multi product	Capacitated	Uncapacitated	Demand	Return Quality	Price	Cost	Capacity	Return quantity	Other
Ramezani, Bashiri, and Tavakkoli-Moghaddam (2013)		*							*		*			*	*		*					*	
Talaei, Moghaddam, Pishvaee, Bozorgi-Amiri, and Gholamnejad (2016)		*							*		*			*	*		*			*			
Torabi, Namdar, Hatefi, and Jolai (2016)									*		*		*		*		*			*		*	facility availability, average disposal fraction
Vahdani, Tavakkoli-Moghaddam, Jolai, and Baboli (2013)		*									*			*	*	*	*			*		*	
Zeballos, Méndez, and Barbosa-Povoa (2015)		*								*		*		*			*					*	
Nikbakhsh, Eskandarpour, and Zegordi (2013)		*					*				*			*	*							*	
Piplani and Saraswat (2012)		*							*		*			*	*							*	Percent of faulty products, warranty fraction of modules and others
Realff, Ammons, and Newton (2004)		*							*			*	*		*				*			*	Volume of carpet collected and price of a key recycled material
Vahdani, Tavakkoli-Moghaddam, Modarres, and Baboli (2012)	*	*			*				*		*			*	*	*							Environmental and system uncertainty
Vahdani and Mohammadi (2015)	*			*					*		*			*	*	*				*	*		
Xu and Zhu (2010)									*			*		*	*					*			
Zeballos, Gomes, Barbosa-Povoa, and Novais (2012)		*								*		*		*	*			*				*	
Total articles (% of total articles)	2 7	15 56	2 7	2 7	6 22	1 4	6 22	3 11	10 37	6 22	14 52	13 48	12 44	15 56	25 93	4 15	20 74	3 11	1 4	10 37	1 4	17 63	6 22

Table 2.3: Stochastic programming and robust optimization papers summary (Industry, problems, number of objectives)

Citation	**Industry**	**Problems**	**Single/Multi-objective approaches**
Cui et al. (2017)	Automotive	Designing a CLSC network under uncertainty	Single objective - cost minimization
Hatefi and Jolai (2014)	Automotive	Integrated forward-reverse logistics network design under uncertain parameters and facility disruptions	Minimizing nominal cost and simultaneously reducing disruption risk
Mahmoudzadeh et al. (2013)	Automotive	Dynamic production/pricing problem	Single objective - profit maximization
Mukhopadhyay and Ma (2009)	Automotive	Procurement and production decisions in remanufacturing	Profit maximization
Vahdani et al. (2012)	Iron and steel	Designing a CLSC network under uncertainty	Bi-objective - minimizing total costs and expected transportation costs after the failure of facilities.
Vahdani et al. (2013)	Iron and steel	Designing a CLSC network under uncertainty	Multi objective - minimization of the total fixed and transportation costs , minimization of the total expected failure costs
Vahdani and Mohammadi (2015)	Iron and steel	Designing a CLSC network under uncertainty	Multi objective - Minimizing total costs and maximum waiting time in queue for products.
Hasani et al. (2012)	Food and high tech electronics manufacturing	Designing a CLSC network under interval data uncertainty	Either minimize total cost or maximize total profit
Keyvanshokooh et al. (2016)	Computer/laptop manufacturers	Designing a CLSC network under uncertainty	Single objective - profit maximization
Meysam et al. (2016)	Electronics, digital manufacturing , automobile, food industry and others	Supply chain configuration and supplier selection	Single objective - Minimizing total fixed and variable costs
Nikbakhsh et al. (2013)	Electronics industry for products such as cell phones and televisions	Design of a closed loop reverse logistics network for a third party logistics provider	Bi-objective - minimize the total fixed and transportation costs, minimizing the tardiness of sending returned products to collection centres
Piplani and Saraswat (2012)	After-sale service for laptops and desktops	Design of a repair and refurbishment network model for forward and reverse flows of modular products.	Single objective - cost minimization
Ramezani et al. (2013)	Electronic, digital equipment, automotive and others	Designing closed-loop logistics network model	Single objective- maximize total profit
Talaei et al. (2016)	Copiers	Designing a carbon efficient CLSC network under uncertainty	Multi objective- Minimizing total costs and carbon-dioxide emissions.

Table 2.4: Stochastic optmization and robust optimization papers summary (Industry, problems, number of objectives, continued)

Citation	Industry	Problems	Single/Multi-objective approaches
Altmann and Bogaschewsky (2014)	Mechanical and plant engineering company	Environmentally conscious CLSC design	Bi-objective - minimizing expected total costs and carbon dioxide equivalents
Dubey et al. (2015)	Case study on - Industrial air conditioner	Designing a responsive sustainable supply chain under uncertainty	Multi objective - cost minimization, reduction of delivery and collection time
Hasani et al. (2015)	Medical devices	Designing a robust closed loop global supply chain network	Single objective - maximize after-tax profit
Kara and Onut (2010)	Paper recycling	Reverse supply chain network design under uncertainty	Single objective - revenue maximization
Realff et al. (2004)	Carpet recycling	Robust reverse production system design	Single objective - Mmaximize net revenue
Zeballos et al. (2012)	Glass	Design and planning of CLSC	Single objective - profit maximization
De Rosa et al. (2013)		Sustainable capacitated facility location problem for two-way product flows	Single objective - cost minimization
Gao and Ryan (2014)		CLSC network design having the ability to cope with varying carbon emission regulations and other uncertain parameters .	Single objective - cost minimization
Pishvaee et al. (2011)		CLSC network design	Single objective - cost minimization
Torabi et al. (2016)		CLSC network design with partial and complete facility disruptions	Single objective - minimize total cost of opening new facilities and expected cost of facility disruptions.
Wang and Huang (2013)		Demand driven disassembly planning problem in CLSC	Determine recycle volume, timing and recovery strategy for different End-of-life items
Xu and Zhu (2010)		Modeling operations in a CLSC with remanufacturing	Single objective - profit maximization
Zeballos et al. (2015)		Designing and planning of CLSC	Multi objective - profit maximization and three risk adverse objective functions

products in an integrated supply chain network with bi-directional product flows and solved a capacitated facility location problem. The authors looked at how an existing forward supply chain can incorporate reverse logistics activities. The RO concept developed by Lee, Dong, and Bian (2010) was used. The model has provisions to select different types of depots (single direction or bi-directional facilities), vary the capacity of facilities, change the location of facilities and consider competition between new and returned products for resources in the network.

Dubey et al. (2015) developed a responsive and sustainable CLSC network model in the presence of demand and return quantity uncertainty. Robust optimization formulations from Soyster (1973); Lin, Janak, and Floudas (2004); Bertsimas and Sim (2004a) were used in this study. The model also considered bill of materials (BOM) for the reverse direction and a finite demand for goods in the secondary market. Interactive fuzzy goal programming approach is the solution methodology used.

To work with the uncertainties surrounding carbon regulations, Gao and Ryan (2014) developed a two-stage, multi-period stochastic programming model incorporating variations in retail demand and product returns. Environmental policy decisions have great repercussions on the entire CLSC network. Even if firms are aware of the type of policy that will be implemented they are unaware of the incentives and penalties of the policy. The model developed is adaptable to carbon tax, and cap and trade policies. The RO approach developed by Ben-Tal and Nemirovski (1999), Ben-Tal and Nemirovski (2000) was used to surmount uncertainties in carbon regulations.

Hasani et al. (2012) developed an agile multi-product, multi-echelon, multi-period CLSC model which incorporated uncertainties in the demand of products and purchasing costs. The uncertainties are dealt with using interval RO introduced by Ben-Tal, Golany, Nemirovski, and Vial (2005). Two Bill of Materials (BOMs) are considered in this study: one for producing new products and the other for substituting products for reuse.

Medical products are perishable and hence Hasani et al. (2015) created a CLSC network to improve customer satisfaction, economic and environmental benefits. Uncertainty surrounding customer demand and product pricing was modelled using the RO technique introduced by Bertsimas and Sim (2004b). The proposed Mixed-Integer Non Linear Program (MINLP) maximized after-tax profit and the model was solved using adaptive variable neighbourhood search heuristic. It was found that as the uncertainty level increases, total inventory cost decreases and the after-tax profits decrease when compared to deterministic models.

Hatefi and Jolai (2014) worked on a robust and reliable integrated logistics network model considering uncertainty in model parameters and uncertainty caused by external disturbances. Uncertainty in model parameters was overcome using Bertsimas and Sim (2004b, 2003) RO approach, whereas facility disruptions due to external factors was dealt with using RO with p-robust constraints.

Kara and Onut (2010) created a model to maximize the revenue of a supply network while handling uncertainty in the demand and volumes of waste paper returned by consumers. Both stochastic programming and robust programming were implemented.

Keyvanshokooh et al. (2016) proposed an MILP for a capacitated CLSC network with a single product in a multi-period setting with uncertainties in demand, transportation costs and return rate of products. Stochastic scenarios based on Latin Hypercube Sampling method were generated for transportation costs and the uncertainty in demand/return rate was modeled using polyhedral uncertainty sets. The paper worked on strategic and tactical decision making by implementing a hybrid robust-stochastic programming approach based on the RO technique introduced by Bertsimas and Sim (2003, 2004b). The model was solved using the accelerated stochastic Benders decomposition method.

Mahmoudzadeh et al. (2013) determined the optimal selling and acquisition prices to assist the manufacturer in overcoming demand and return rate uncertainty. A robust optimization model based on quadratic programming was used to achieve profit maximization in the CLSC.

Meysam et al. (2016) considered variations in demand, transportation and processing costs when developing an MILP for the CLSC configuration and procurement management. The model used RO to minimize the total cost of the supply chain by finding appropriate suppliers, deciding order quantities from selected suppliers, location of new facilities and quantities of products to be transported between them. Box, Polyhedral and (Interval + Polyhedral) uncertainty sets were employed in this model. The three uncertainty sets provide decision makers flexibility on the level of robustness to be incorporated in the network.

Mukhopadhyay and Ma (2009) employed two-stage stochastic analysis to find optimal production and procurement strategies for a CLSC under demand and quality uncertainty when new and remanufactured parts are interchangeable in the production process. The quantity of new parts to be ordered, quantity of returns to be procured and the quantity of finished products to be manufactured are determined by the model.

Pishvaee et al. (2011) proposed a deterministic MILP followed by its RO counterpart based on Ben-Tal and Nemirovski (1999, 2000, 2008); Ben-Tal et al. (2005) to overcome the challenges due to the uncertainties in returned goods, demand for recovered goods and transportation costs. The paper integrated supply chain activities in the forward and reverse direction, created a framework to support both open and closed-loop networks.

Ramezani et al. (2013) proposed a robust model for designing a CLSC with multiple products, multiple stages and uncertainties in the demand and return rates of products. The model has three echelons in the forward and reverse direction with the core objective of maximizing the total profit while finding the capacity of facilities and the quantity of products to be transported between facilities. Scenario relaxation algorithm reduced the time to obtain robust solutions.

Talaei et al. (2016) presented a CLSC network design model for facility location and allocation for a multi-product setting. The total cost of the CLSC as well as the total carbon dioxide emissions from activities such as transportation between facilities, construction of new facilities and production process are minimised. A robust fuzzy programming model handled the uncertainties in variable costs and demand rate. The ϵ-constraint approach was used to solve the proposed model.

Torabi et al. (2016) posited a CLSC network model which considered uncertainty in some modeling parameters. P-robust constraints control the effects of facility disruptions by balancing the costs of a disruption with the nominal cost of the network. Fuzzy numbers are used to categorize the extent of facility disruptions. The authors put forth a mixed integer possibilistic programming model which minimize the total cost associated with opening of a new facility and costs encountered during the disruption of facilities by extending the work done by Xu and Zhou (2013).

Vahdani et al. (2013) developed a robust CLSC network design model that considered traditional objectives and reliability considerations simultaneously. A bi-objective MILP was proposed to solve a network consisting of multiple products, suppliers, stages and facilities. A hybrid solution approach derived from fuzzy possibilistic, interval and chance-constraint programming techniques was utilized.

Zeballos et al. (2015) proposed an MILP for the design and planning of CLSC networks. Uncertainty surrounding the demand and supply of products was overcome using a multi-stage stochastic approach. Profit maximization, coping with uncertainties and creating network performance stability were the chief objectives of the model which permitted the opening/closing of facilities in different time periods. Three risk adverse objective functions such as linear measure of the profit variability, modified linear measure of the profit variability and conditional value at risk were considered to increase the efficiency of the model under uncertainty.

Nikbakhsh et al. (2013) developed a robust bi-objective MILP model for studying the operations of a third party post-sales service provider. The quantity of defective product returns is uncertain in this study. Transformation from a bi-objective optimization to a single objective optimization was achieved using the ϵ constraint method.

Piplani and Saraswat (2012) dealt with uncertainty in return quantity, percent of faulty returned products, percent of products under warranty, demand growth and supply of returned products. The authors used a min-max robust optimization approach developed by Kouvelis and Yu (1997). The MILP model used a cost minimization approach to locate facilities and find the product flows. Supply of faulty modules was found to be the key parameter affecting the network.

Realff et al. (2004) designed a reverse production infrastructure system using techniques from Kouvelis, Kurawarwala, and Gutierrez (1992). The paper aimed to find at least one infrastructure configuration that would be feasible under all cases of uncertainty. The MILP model aimed at finding the most suitable raw materials to be recovered, recycling tasks to be performed, location and capacities of facilities and the mode of transportation between facilities to maximize profit.

Zeballos et al. (2012) posited a two stage scenario-based modeling approach for the design and planning of a CLSC. Uncertainty in the quantity and quality of returned products was considered in this study which permitted the analysis of returned products under various scenarios. Planning of supply of raw materials, production of new products, transportation, storage and collection of returned products over several sub-periods was also determined.

The next type of uncertainty which is widely covered is cost uncertainty. Around 37 % of the articles in this category account for cost uncertainty.

Vahdani and Mohammadi (2015) addressed the issues of uncertainty in the total costs of a CLSC and the waiting time in a queue for products in the iron and steel industry. A bi-directional capacitated facility location model was developed. The proposed model can assist in the development of CLSC networks containing different types of products. M/M/c queueing system is used and a new hybrid solution approach combining interval and stochastic programming, robust optimization and fuzzy multi-objective programming was introduced. Special solution procedures utilizing self-adaptive imperialist competitive algorithm meta-heuristic was proposed. By optimizing the total costs to the CLSC a more centralized network was generated but optimizing the waiting time created a decentralized network.

Xu and Zhu (2010) studied remanufacturing operations in a CLSC where returned parts can be refurbished and used in place of new parts in the manufacturing process. The manufacturer is responsible for the proper recovery and disposal of returned products. Three uncertain parameters are considered in this CLSC model: 1) costs associated with disassembling returned products 2) costs of refurbishing disassembled parts 3) disposal costs of disassembled parts.

Uncertainty in return quality, price and capacity has received less coverage from authors. Uncertainty in return quality is covered by Hatefi and Jolai (2014), Mukhopadhyay and Ma (2009) and Zeballos et al. (2012). While uncertainty in price has been covered by Realff et al. (2004) and uncertain capacity has been covered by Vahdani and Mohammadi (2015).

Vahdani et al. (2012) designed a CLSC network model for the iron and steel industry. The robust M/M/c model developed can deal with environmental and system uncertainties and has the dual objective of minimizing the total cost of the network and expected cost of failure of the facility. A hybrid solution methodology is proposed by amalgamating concepts from queueing theory, robust optimization and fuzzy multi-objective programming.

We now classify papers overcoming uncertainty based on the industry areas and applications considered. (Table 2.3 and 2.4 provide a summary of articles described below).

The following industrial areas have been considered.

- **Automotive Industry**: Cui et al. (2017) studied a small (12 node) and a large (20 node) problem in the automotive industry with small, medium and large demand values. Hatefi and Jolai (2014) proposed a model for use in the automotive sector which may be exposed to uncertain supply, demand parameters and occasionally to natural disasters. Mahmoudzadeh et al. (2013) worked on a dynamic production/pricing problem faced by automotive manufacturing and remanufacturing units. Mukhopadhyay and Ma (2009) developed two scenarios based on random yield rate (fraction of returned products which can be remanufactured) and demand rate for a real-world automotive engine remanufacturer. The engine remanufacturer stores large quantities of parts as there are a variety of engines, variable delivery times for new and remanufactured parts and unpredictability in the type of returned engine.

- **Iron and steel Industry**: Vahdani et al. (2012), Vahdani et al. (2013) and Vahdani and Mohammadi (2015) studied cases in the iron and steel industry and designed CLSCs with forward supply chain elements including ore suppliers, iron and steel manufacturers, metal manufacturing facilities etc., and scrap collection and processing facilities in the reverse direction.

- **Electronics Industry**: The model developed by Nikbakhsh et al. (2013) is applicable in the post sales consumer electronic industry for cell phones and televisions. Piplani and Saraswat (2012) worked on a repair and refurbishment network model for electronic products. They studied a case in the computer industry and found that significant cost benefits can be gained on locating distribution centres close to OEMs and repair vendors (RVs). Talaei et al. (2016) solves a problem in the copiers industry. The CLSC model developed by Ramezani et al. (2013) has 4 layers (suppliers, distributors, plants and customer zones) in the forward direction and 4 layers (repair, disposal centres, etc.) in the reverse directions. The model is applicable automobiles, electronics and digital equipment manufacturing. Meysam et al. (2016) can be used in industries where returned products are disassembled for their components and usable components if any can be incorporated in new products. Their model is applicable to the automotive industry, electronic products, etc. Hasani et al. (2012) proposed models for the food and high tech electronics manufacturing sectors where there are time dependent parameters such as the cost of the product and the warehousing lifetime period.

Altmann and Bogaschewsky (2014) used data from a world-leading mechanical and plant engineering company to test their model. The effects of supply chain design decisions on the environmental standing of the supply chain network was gauged. It was found that changes in facility location, logistics, supplier selection, investment planning, production allocation and capacity planning, and inventory planning can bring great environmental benefits.

Dubey et al. (2015) implemented their model in an industrial air conditioner manufacturing company. Questions related to the current state of CLSC network design literature, use of deterministic models to capture uncertainty, environmental benefits, social issues and methods to quantify uncertainty were given importance in this research work.

Hasani et al. (2015) studied a major medical device manufacturer. The manufacturer wanted to expand its reach in neighbouring countries and hence had to adapt to the Economic Cooperation Organisation Trade Agreement, each countries tax rates, import tariffs and transfer pricing limitations. Under conditions of uncertainty in demand and procurement costs, the proposed model generated lesser after-tax profit as compared to a deterministic model.

Kara and Onut (2010) worked on a two-stage stochastic reverse supply chain network model for a large scale paper recycler. The recycler has the capacity of handling 1,200,000 tons of paper each year. The model found the optimal location for the recycling facilitiy and flow between the nodes in the network.

Realff et al. (2004) considered a case in the carpet recycling industry where robust optimization helped in overcoming variations in the volume of carpet and price of a valuable raw material (hexamethylene diamine) collected. Robust optimization was found more suitable in this case as the systems cannot be changed owing to extreme costs, high uncertainties and lack of historical data.

Zeballos et al. (2012) studied a Portuguese glass firm. In the case study the returned products were classified according to their quality as good, medium or bad before they were sent for disposal or made part of the new product stream. Improvement in the returns quality improved the performance of the network and increased profitability, as the network has a lower dependence on raw materials.

Summary of stochastic and robust optimization models

Researchers have proposed mathematical models to overcome uncertainty in the total costs of the CLSC network, waiting time in the queue for products, transportation costs, demand and return rate of used products, processing costs, product pricing, purchasing costs, percent of faulty returned products, percent of products under warranty, carbon regulations, uncertainties due to natural or man-made disasters such as earthquakes, tsunamis or terror attacks and costs associated with disassembling, refurbishing, disposing products.

Uncertainty in demand, return quantity and cost has received considerable coverage from researchers but uncertainty in return quality, price and capacity has not been covered so extensively. The automotive, iron and steel and electronics industry has been covered by a good number of scholars.

Robust optimization techniques were mainly adapted from the work of Bertsimas and Sim (2004a, 2003); Ben-Tal and Nemirovski (2008, 1999); Ben-Tal et al. (2005); Ben-Tal and Nemirovski (2000); Soyster (1973); Mulvey, Vanderbei, and Zenios (1995). Robust techniques provided solutions which were pricier than those obtained from deterministic models as it created solutions which were feasible for all possible realizations of uncertain parameters.

This section presented a review of articles on stochastic and robust optimization models. The next section is a review of quality and reliability issues in CLSCs and RLs.

2.6 Quality and reliability

Returned products have different quality and reliability levels based on customer usage. Among returns we may find products which have never been used or find ones that are completely destroyed beyond repair. Having the ability to predict the quality and reliability of returned products can greatly benefit the reverse logistics process. It can enable decision makers to establish facilities and allocate sufficient resources for remanufacturing/refurbishing/recycling operations. We now classify articles considering product quality and reliability based on their modeling approach and settings (number of periods/products/components).

In this subsection, articles contain models with single period, single component products with quality grading and quality pricing considerations. Table 2.5 provides a summary of the articles described below.

Behret and Korugan (2009) developed a policy for balancing a hybrid manufacturing and remanufacturing system throughput with demand. As the system is stochastic in nature, backorders and inventory cannot be avoided. The system faced uncertainty in the quantity, timing and quality of the returned products. Uncertainty affected the quantity of raw materials ordered, material recovery rate and time for processing returned products. Based on the remanufacturing effort needed, the returns are classified as good, average and bad quality. A multi stage inventory control simulation (using ARENA simulation program) models the uncertainty in quality and balances the hybrid system. Under different cost scenarios and when facing high returns, quality grading of returned products is beneficial to system. Classifying returned products created multiple control points in the system and an increase in variance resulted in increased cost savings. On the basis of a numerical example, under high return rates, it was showed that a system with graded returned products had 8 % more cost savings

Table 2.5: Reliability and quality papers summary (1)

Citation	Method		Quality		Settings						Problem solved	Industry examples
	MILP	Other	Grading	Pricing	Single Period	Multi Period	Single component	Multi component	Single product	Multi product		
Behret and Korugan (2009)		Multi stage inventory control model	*	*	*		*		*		Modeling and analysis of a hybrid manufacturing-remanufacturing system	
Dwicahyani, Jauhari, and Kurdhi (2016)		Deterministic inventory model	*	*	*		*		*		Integrated inventory model in a CLSC with inspection, sorting and waste disposal	
Teunter and Flapper (2011)		Simple closed form expression and newsboy-type solutions	*	*	*		*		*		Acquisition and remanufacturing decisions under quality uncertainty	Mobile phone
Zou and Ye (2015)		Game theory	*	*	*		*		*		Pricing and supply chain coordination strategies considering product design and quality of returned product	
Radhi and Zhang (2016)		MINLP	*	*	*		*			*	Configuration of remanufacturing networks under conditions of return quality and demand uncertainty.	Tyre remanufacturing or retreading industry

as compared to a system where there was no gradation of products.

Dwicahyani et al. (2016) developed an integrated inventory model for a CLSC. They introduced a special variable to quantify the quality levels of a used product. The developed deterministic model considered both remanufacturing and refurbishing recovery processes. Multiple remanufacturing and production cycles were used to find the optimal solution. The joint profit of suppliers, manufacturers and retailers was maximized in this model along with finding the ideal production and replenishment policies.

The quality of acquired cores affects the remanufacturing process hence Teunter and Flapper (2011) simultaneously analyzed acquisition and remanufacturing decisions. Optimal acquisition decisions are enabled by considering multiple quality grades and multinomial quality distributions for the acquired products. Both deterministic and uncertain demand were studied in this research. Total expected cost of acquired cores in the deterministic demand case was found from a closed-form expression while the case including both uncertainty in return quality and demand was solved by implementing newsboy-type optimality conditions.

Zou and Ye (2015) studied the pricing and co-ordination strategies for single-manufacturer-single-retailer CLSC. Manufacturing costs are uncertain due to the quality of the returned product and the proportion of used components which can be added to a new product. Game theory was implemented in this model. Under centralized and decentralized model scenarios, optimal solutions for the manufacturer and retailer was obtained. The threshold for the proportion of used components in a new product was also discussed. It was found that there exists a negative correlation between the wholesale price and retail price while there is a positive correlation between the recycling rate and the profit obtained from the CLSC. Centralized decision making was found to be more efficient as compared to decentralized decision making.

We now study Radhi and Zhang (2016) who created a model with multiple products while keeping other settings similar to the previous articles. Radhi and Zhang

(2016) is one of the few works which studied remanufacturing operations where remanufactured goods are sold at a discounted price as compared to new products. This study developed a quality grading tool and an acceptance strategy for used products under conditions of quality uncertainty. The quality of the returned products is considered to be normally and exponentially distributed. A MINLP model was developed to find the optimal network for the remanufacturing operations with return quality decisions. The model has been applied to the tyre remanufacturing industry. They suggest that a higher number of returns and quality uncertainty can be viewed as an opportunity to increase profit while reducing remanufacturing costs.

Articles containing models with single period, multiple component products and quality grading and quality pricing considerations are now studied. Table 2.6 provides a summary of the articles described below.

Bhattacharya and Kaur (2015) developed a single period multistage CLSC model which simultaneously considered the manufacturing of new products and remanufacturing of returned products. Remanufacturers acquire used products from customers and are paid different prices based on the quality grade of the returned product. Based on the demand of the repair/recycling stage, groups of graded products are sent to different facilities. After repairing, refurbishing, recycling the used products are incorporated in the forward supply chain. The authors focus on profit maximization in the non-linear optimization problem and studied an auto parts supplier. The key decisions made in this study include finding the optimum sale price of new products and the percentage of returned products of varying quality grades that should be pulled in different stages of the reverse supply chain (RSC). Pulling optimum quantity of returned products of different grades from the collection centre by different stages of the RSC was found to reduce uncertainty and improve CLSC efficiency.

Chen et al. (2015) proposed a recycling strategy for printer cartridges in Hong Kong. Used cartridges were classified into good and poor quality grades. The main objective of the model was to solve 1) the optimization of the location and allocation of facilities 2) find the optimal transport route and delivery quantities in the CLSC

Table 2.6: Reliability and quality papers summary (2)

Citation	Method		Quality		Settings						Problem solved	Industry examples
	MILP	Other	Grading	Pricing	Single Period	Multi Period	Single component	Multi component	Single product	Multi product		
Bhattacharya and Kaur (2015)		Non-linear optimization	*	*	*			*	*		Maximizing the profitability of a multi-stage CLSC	Automobile parts
Chen, Chan, and Chung (2015)	*	Modified two stage GA	*	*	*			*	*		To reduce the pollution caused due to waste cartridges	Printer cartridge recycling
Krikke (2011)	*		*	*	*			*	*		Decision framework for optimizing CLSCs , includes location-transportation and disposition decisions	Copiers
Li (2013)		Quantitative method for evaluating economic, product quality and ecological parameters	*	*	*			*	*		Evaluating the production system in CLSC	Soy milk machines manufacturing company
Örsdemir, Kemahlıoğlu-Ziya, and Parlaktürk (2014)		Demand model	*	*	*			*	*		Competition between an Original Equipment Manufacturer (OEM) and an independent remanufacturer	Cartridges and copiers
Jiang, Zhou, Zhang, Wang, Cao, and Tian (2016)		GA	*	*	*			*	*		Optimization of remanufacturing process planning	Lathe machine
Das and Chowdhury (2012)		Mixed integer programming	*	*	*			*		*	Reverse logistics planning with modular product design	
Giglio and Paolucci (2014)	*		*	*	*			*		*	Determine the production lots, quantity of new parts and returned products to be acquired.	
Ghayebloo, Tarokh, Venkatadri, and Diallo (2015)	*		*	*	*			*		*	CLSC network design	

network 3) recycling alternatives for returned products based on their quality and materials extracted. The proposed MILP model was solved using Lingo for small instances of the problem and GA was implemented for larger instances of the problem.

Krikke (2011) proposed a decision support framework for analyzing disposition and location-transportation decisions in a CLSC network and the authors applied the model to a global printing company “CopyDoc”. It was shown that substitution of new products made from virgin materials by repaired, refurbished or remanufactured products decreases the carbon footprint of organizations. Substitution can be increased by having access to a variety of recovery options for returned products, integrating forward and reverse logistics, choosing optimal facility locations and transport routes.

Li (2013) developed a framework consisting of economic, product quality and ecological modules for evaluating the production system for a CLSC. Due to the dynamic characteristics of the reverse supply chain, mathematical probability theory was used for product quality evaluation. Reliability and time-utility value of the product is used as a basis for the concept of product quality. Simulations and a case study based on a household appliance (e.g. soy milk machines) manufacturer was used for demonstrating the proposed evaluation system. Procurement strategies and quality of recycled components played a critical role in the evaluation model of the CLSC.

Örsdemir et al. (2014) studied competition between an OEM and an independent remanufacturer (IR). This research challenges the general belief that remanufacturing is beneficial to customers and the environment. The OEM controls the quality of the product which has a direct impact on the IR operations. Under conditions of equilibrium and if the OEM has a greater competitive advantage over the IR, the OEM leverages its product quality. If the IR has a greater competitive advantage as compared to the OEM, then the OEM tends to limit the number of cores available in the secondary markets. This research finds the impact of remanufacturing operations conducted by an IR on customers and the environment. It was found that either the IR or the OEM should have a great competitive advantage. When both are equally competitive then there is an intense competition between the two and the quantity of new and remanufactured products increase in the market with greater environmental and social repercussions. Remanufacturing by OEMs is encouraged in this study to promote environmental and customer well-being.

Jiang et al. (2016) worked on optimizing the remanufacturing process by achieving a dual-objective of improving product reliability and decreasing process cost. Quality of cores has an impact on the remanufacturing tools and hence the failure rate of the remanufacturing operations serves as a barometer to measure reliability. The authors implemented GA to solve the proposed model. Data from a lathe machine was used to test the proposed model. Apart from assisting decision makers in remanufacturing process planning, the proposed model can act as a tool for high reliability remanufacturing at an economical cost.

The main change in the following articles as compared to previous ones is the use of multiple products in the model.
Das and Chowdhury (2012) created a mixed-integer program (MIP) model for maximizing the profit of an integrated reverse logistics system. This study considered modular product design which reduced the effort and cost in the recovery process. The other benefits of modular product design are the reduction in lead time for producing new and recovered products, possibility of offering customized products at lower costs. Three product grades are offered to customers based on the quality of modules present in the item. Effort has also been made to offer customers better warranty policies for recovered products. Customer-friendly collection practices are followed as retailers are responsible for the collection of used products and an integrated network of recovery service providers are responsible for the recovery efforts. To enhance sustainability of the supply chain, incentives are offered to customers to return products, agreements are made related to the maximum quantity of products to be collected by retailers and the minimum percentage of recovered modules to be included in certain products.

Giglio and Paolucci (2014) worked on a hybrid manufacturing-remanufacturing system and solved a multi-item, multi-stage lot sizing problem. The papers focused on determining the number of products to be manufactured, quantity of new parts to be purchased, quantity of old parts to be recovered from returned products and number of returned products to be purchased. The quality of the returned products has a bearing on the remanufacturing process time and the quantity of recovered parts. Hence returned products are graded based on their quality using a set of integers. A numerical example consisting of 1150 variables and 560 constraints was used to showcase the applicability of the proposed model.

Ghayebloo et al. (2015) developed a bi-objective CLSC network design model for profit and greenness maximization. Greenness score depends on the part/material reliability and its green characteristics. In the proposed model the value of green products in the network is maximized while keeping a check on the costs incurred. To portray the trade-off between profit and greenness, Pareto optimal solutions were found using the ϵ constraint method.

Articles containing models with multiple periods and including quality grading and quality pricing considerations are now studied. We first study models with single products and single components followed by models considering multiple products with multiple components. Table 2.7 provides a summary of the articles described below.

Remanufacturing firms try to maintain a steady stream of returned products/cores by developing product leasing strategies with customers and offering them a trade-in credit for a used item on the purchase on a new one. Leasing new products to customers was found to be more effective for acquisition of used products but the quality of the cores is uncertain. Denizel et al. (2010) focused on overcoming quality uncertainties and capacity constraints to achieve a stable remanufacturing process. A stochastic programming model was developed under a multi-period setting to generate feasible solutions under varying quality levels of the returned cores. Used products are classified using a scale from best to worst quality based on a pre-defined probability. The model determines the number of cores of different grades that need to be

Table 2.7: Reliability and quality papers summary (3)

Citation	Method		Quality		Settings						Problem solved	Industry examples
	MILP	Other	Grading	Pricing	Single Period	Multi Period	Single component	Multi component	Single product	Multi product		
Denizel, Ferguson, et al. (2010)		Stochastic programming	*	*		*	*		*		Remanufacturing production planning under conditions of returned product quality uncertainty	Mailing equipment
Nenes and Nikolaidis (2012)	*		*	*		*	*		*		Optimization of decisions related to procurement, remanufacturing, salvaging and stocking	Cell phones
Jayaraman (2006)		Linear programming	*	*		*		*		*	Production planning and inventory control	Cell phone
Ramezani, Kimiagari, Karimi, and Hejazi (2014)	*	Fuzzy mathematical programming	*	*		*		*		*	CLSC network design	Electronics, digital equipment and vehicles industries
Sheriff, Nachiappan, and Min (2014)		Capacitated Routing and Allocation with Balancing-Multiple Products (CRAB-MP).	*	*		*		*		*	Location, allocation and routing decisions in a reverse logistics network	Plastic recycling industry (bottles)
Yamzon, Ventura, Guico, and Sy (2016)		MINLP	*	*		*		*		*	Collection of returned goods, incentives offered and recover options for CLSC	Electronics

remanufactured, the quantity of cores that need to be stored in inventory for future use and the quantity of cores that need to be salvaged. It was found that a firms profit is influenced by the shape of the production cost curve in relation to the core quality, and the money invested in grading and salvaging used products.

Nenes and Nikolaidis (2012) developed an MILP model for optimizing the quantities of items that should be procured, remanufactured, stocked and salvaged. The proposed model has the ability to incorporate multiple supplier, multiple periods and varying quality levels of returned goods. This paper fills a gap in the industry by creating a practical and quantitative tool which supports decision makers in assessing returned products. An illustration for cell phone, digital camera and printer manufacturing companies which offer high quality remanufactured products as alternatives to new products is provided. A set of integers was used to reflect the returned product quality and uncertainty in information regarding reverse logistics was overcome using simulation analysis. The proposed MILP model was more efficient as compared to the strategy of using a single-period model multiple times.

Next, we now consider models dealing with multiple products and multiple components. Jayaraman (2006) developed a mathematical programming model (Remanufacturing Aggregate Production Planning) for the production planning and control of CLSCs. The model finds material recovery rates, quantity of replaced parts/materials and associated costs, and workloads at different facilities. The model is suitable for medium to long term planning horizons and the objective is to decrease the total cost per remanufactured unit. Decisions related to the quantity of cores acquired, disassembled, remanufactured and disposed are also studied. Data from a cellular handset remanufacturer (ReCellular) is used to validated the proposed mathematical model. ReCellular developed 6 nominal quality levels to gauge the condition of returned phones. The study focused on designing products for recovery while creating a balance between the investment in recovering parts/materials and savings obtained from recovery efforts.

Ramezani et al. (2014) designed a CLSC network over a multi-period horizon considering multiple periods and multiple echelons. This research is unique as it simultaneously works with three objective functions 1) maximizing the total supply chain profit 2) enhancing customer service levels by minimizing delivery time for products in the forward and reverse directions 3) reducing the number of defective parts acquired from suppliers, there by maximizing six-sigma quality levels.

Sheriff et al. (2014) addressed the recycling activities for plastic bottles by developing a Capacitated Routing and Allocation with Balancing Multiple Products model. The model solves three major objectives: 1) Finding the optimal locations of Initial Collection Points(ICPs) and Centralized Return Centres (CRCs) 2) Assigning customers to appropriate ICPs and CRCs 3) Finding the optimal transportation route between different entities in the network. There is also provision to provide varying incentives to customers based on the quality of products returned. This is one of the initial studies which considered clustering in the RL process and simultaneously created a solution to location, allocation and routing problems.

Yamzon et al. (2016) developed a MINLP model for a CLSC to support decisions regarding collection activities, types of incentive offered for returned products and recovery options. A variety of incentives such as discounts and cash rebates can increase the quantity and quality of product returns. Returned products received a quality grade between q low (0) and q high (100) and are either refurbished, remanufactured, cannibalized or disposed. The model was subjected to scenario analysis and conditions were identified for various incentive offerings. Rebate-type incentive was found to be more favourable than discount based incentives. Under conditions of high collection targets and higher recovery costs compared to selling prices, rebate-type incentives are preferred. Discount based incentives are preferred in the luxury goods industry where the selling price is high and demand is low. When the stock out costs of the secondary market are high then higher incentives are offered to obtain better quality returns.

Next, we study articles with a variety of methods, quality considerations and other settings. Table 2.8 provides a summary of the articles described below.

Table 2.8: Reliability and quality papers summary (4)

Citation	Method		Quality		Settings						Problem solved	Industry examples
	MILP	Other	Grading	Pricing	Single Period	Multi Period	Single component	Multi component	Single product	Multi product		
Ferguson, Guide, Koca, and Souza (2006)		Linear programming	*			*			*		Production planning for remanufacturing	Mailing equipment
Guide, Jayaraman, and Linton (2003b)		Case study approach									Contingency planning in CLSC	Kodak, Xerox and US navy depots
Huang, Yi, Shi, and Guo (2015)		Modal interval arithmetic and scenario based methods	*	*			*			*	Characterize quality uncertainty of used products and model dynamic decision in remanufacturer driven CLSC with multidimensional reverse channels	Construction machinery
Jin, Hu, Ni, and Xiao (2013)		Markov decision process	*	*				*	*		Policy making considering modular product reassembly in remanufacturing	Batteries of electric vehicles
Li, Xiang, and Qu (2015a)		Mathematical probability theory	*		*			*	*		Product quality problem in CLSC	
Östlin, Sundin, and Björkman (2008)		Qualitative approach	*	*							The advantages and disadvantages of 7 closed-loop relationships for collecting cores for remanufacturing	Automotive, toner cartridges
Robotis, Boyaci, and Verter (2012)		Two-period model framework	*			*					Study the effects of used product quality uncertainty on investment decisions related to product re-usability and used goods collection efforts	Cell phones

Ferguson et al. (2006) studied the production planning and control problem for remanufacturing firms which receive returned products of varying quality grades. It was found that as the quality of returned products decrease the remanufacturing cost increases. Remanufacturing increases the product value. The holding costs are high for remanufactured goods and hence companies remanufacture-to-order. Though the articel has considered the case of Pitney-Bowes, a remanufacturer of mailing systems, the proposed model can be applied to remanufacturers in other industries. Pitney-Bowes gets a large number of returned products as they lease around 90 % of their equipment. The returned products are graded as good, better and best after which they are either recycled for obtaining raw materials, disassembled for their parts or remanufactured.

Guide et al. (2003b) takes the contingency planning approach and addresses the issues in production planning and control of a CLSC. Though there are a number of similar activities which are required for the successful planning and control of the CLSC, managerial concerns differ across supply chains. Case studies from Kodak, Xerox Europe and the US Navy Depot are used to represent Remanufacture-to-stock, Reassemble-to-order and Remanufacture-to-Order strategies respectively. Hayes and Wheelwrights product-process matrix framework was used to analyze the similarities and differences in the three cases. The three firms are analyzed based on returns volume, returns timing, returns quality, product complexity, testing and evaluation complexity, and remanufacturing complexity. The framework can assist decision makers in focusing on the key parameters and critical information while designing a CLSC with product recovery.

Huang et al. (2015) considered construction equipment remanufacturing and developed a model for a remanufacturer driven CLSC. Used products are tested and classified into three grades (high grade, middle grade and low grade) depending on the amount of remanufacturing effort required on the product. Quality of returned products is uncertain before testing. To deal with this uncertainty, modal interval arithmetic method is used to find the optimal pricing and collection strategy during remanufacturing. The results from the modal interval arithmetic method are validated by comparing them with the results obtained from a scenario based analysis. Envelope curves are used to ensure robust decision making under situations of quality uncertainty of returned products.

Jin et al. (2013) addressed the issues faced by remanufacturers in modular product reassembly. This research was motivated by the remanufacturing efforts conducted on the battery of an electric vehicle but is applicable in industries with modular product structure. Benefits of an optimal reassembly-inventory policy, module substitution, and upkeep of module inventories of different qualities are found. Markov decision process was implemented in this research and the optimal reassembly policy was found to be state-dependent multiple threshold-based. Two heuristic policies were discussed for larger problems. The optimal reassembly policy with module substitution and threshold-based assembly control was found to be superior to an exhaustive reassembly policy.

Based on reliability and the time utility value of a product, Li et al. (2015a) develops the concept of product effectiveness. Considering the variations in reverse logistics and using mathematical probability theory, quantitative models are developed to describe product effectiveness. In the model developed, a manufacturer follows fixed production cycle and returned products can only be recycled once before they are removed from the CLSC. If the returned products are in good condition, they are reused directly else they are repaired before adding them to the supply chain.

Östlin et al. (2008) focused on the remanufacturing industry and tried to unearth as well as manage the various relationships that exist between remanufacturers, customers and core suppliers. Based on the level of trust and collaboration between entities (customer and manufacturer), seven relationships have been researched in detail. The relationships are ownership based, service-contracts, direct-order, deposit-based, credit-based, buy-back and voluntary-based.

Robotis et al. (2012) studied the impact of the uncertain quality of returned goods

Table 2.9: Reliability and quality papers final summary (5)

Citation	**Method**		**Quality**		**Settings**					
	MILP	**Other**	**Grading**	**Pricing**	**Single Period**	**Multi Period**	**Single part**	**Multiple parts**	**Single product**	**Multi product**
Total articles	6	23	26	23	15	8	8	15	15	9
%of total articles	22	85	96	85	56	30	30	56	56	33

Table 2.10: Papers with reliability concepts

	Reliability	
Citation	Assessment method	Failure modeling
Li (2013)	Reliability function of new, repaired and directly reused components are implemented.	Components fail independently and failure rate is used
Li et al. (2015a)	Reliability function of new, repaired and directly reused components are implemented.	Failure rate is used
Jiang et al. (2016)	Failure rate of remanufacturing operations represents reliability	
Ghayebloo et al. (2015)	Two reliability levels have been defined	

in investment decisions linked to product re-usability and used product acquisition. The authors have created a two-period model for a firm conducting manufacturing and remanufacturing operations. Only new products are sold in the first period of the model. In the second period, new as well as remanufactured products are sold. Inspection procedures are graded into 2 categories based on the quality of inspection. Though uncertainty in the quality of returned products is considered to be an obstacle by enterprises, this research shows that it need not be the case and with the right inspection tools, quality uncertainty can be overcome and good investment decisions can be made.

Summary of product reliability and quality concerns in CLSC

Research focuses on areas like finding the number of new and remanufactured items to be produced, number of new parts to be procured, number of old components to be salvaged from returned products, number of items to be stocked, optimal transport routes, optimal location and allocation of facilities, relationships between entities of the CLSC, maximizing six-sigma quality levels, design for recovery, solving production planning and control problems in remanufacturing, modular product design and competition between an OEM and IR.

From the summary Tables 2.9, 2.10 it can be seen that there is a lot of emphasis on quality grading and quality pricing but the concept of reliability in CLSC was studied by only 4 articles. Product leasing, trade-in-credit and other strategies adopted by manufacturers to entice good quality returns from customers was proposed. MILP models, scenario based modeling, GA, stochastic programming, heuristic policies were the major models employed. Remanufacturing of construction equipment, electronic products, glass, auto parts, household equipment, printer cartridges, plastic bottles, tyres, cell phones, mailing systems, electric vehicle batteries were discussed. Future research opportunities could include a greater focus on models with multiple products and multiple periods. Researchers can also focus on finding ways to assess the reliability of returned products.

This section presented a brief review on product reliability and quality concerns in CLSC. The next section is a review of models which consider the carbon emissions generated in the CLSC.

2.7 Carbon emissions

Carbon emissions have an adverse impact on the environment. Hence environmentalists and regulatory authorities have been persuading organizations to reduce their emissions. A variety of carbon reduction policies have been proposed by governments the world over. Incorporating emission policies in CLSCs make them even more rewarding.

The three common carbon emission policies are the carbon cap, carbon tax and carbon cap-and-trade. Under carbon cap policy a firm is allowed to emit up to a certain quantity of emission, under the carbon tax policy a firm is taxed based on the carbon emissions generated and the carbon cap-and-trade policy enforces a cap on the maximum emissions that a firm can generate while at the same time rewards (penalizes) firms when the emissions are below (above) the permitted levels. (Fareeduddin, Hassan, Syed, and Selim, 2015)
In the following articles we look at how carbon emission constraints are assimilated into CLSCs. Following papers are classified based on the carbon policy implemented.

In this subsection we focus on the articles implementing the carbon cap policy. Table 2.11 summarizes the articles described below.
Darbari et al. (2015) and Kafa et al. (2015) are the only articles which consider carbon cap policy. Other articles consider a combination of carbon cap with other emission policies.

Darbari et al. (2015) proposed an integrated CLSC network model to help decision makers find the right supplier, minimize the cost of the network operations and control carbon emission due to transportation in the network. Working with EOL and EOU products entails high uncertainties. To effectively overcome these uncertainties, the model uses fuzzy multi-objective optimization approach. Suppliers are first evaluated using Analytical Network Process (ANP) based on the emissions generated, cost effectiveness, quality of products and their performance. Using the travelling salesman problem approach and by grouping hybrid distribution-cum-collection (HDC) centres by K-means clustering technique the model aimed to transport goods using a single truck on an optimal route.

Kafa et al. (2015) presented a methodology to select a supplier and a third-party reverse logistics (3PRL) provider based on sustainability criteria. The criteria are further grouped into economic, social and environmental aspects. As its a multi criteria decision making problem, fuzzy AHP-PROMETHEE concept was used to evaluate suppliers and 3PRL providers. The results from Fuzzy AHP-PROMETHEE is feed to an MILP which created a CLSC network. A weighted max-min approach is used to

Table 2.11: Carbon emission based papers summary (carbon cap and carbon tax policy)

Citation	Carbon emissions measured during									Carbon policy used			Industry
	Manufacturing of raw material/sourcing	Manufacturing of final/recyclable product	Product storage and handling	Sales and product usage	Energy mix used/power consumption	Remanufacturing/Recycling/Recovery	EOL/Disposing product/landfilling	Transportation (Forward/Reverse)	Total Emissions for the CLSC	Carbon cap	Carbon tax	Carbon Cap and trade and other policies	
Darbari, Agarwal, and Jha (2015)								*		*			Printers
Diabat, Abdallah, Al-Refaie, Svetinovic, and Govindan (2013)		*	*		*			*	*	*		*	
Fareeduddin et al. (2015)	*	*	*			*		*		*	*	*	
Juhong, Haiyan, Hongshuai, and Liting (2013)									*	*	*		Notebook computer manufacturing
Kafa, Hani, and El Mhamedi (2015)	*								*	*			Washing Machine Manufacturer
Tao, Guang, Hao, Song, et al. (2015)		*				*				*	*		
Xu, Liu, and Han (2015)		*								*		*	
Kannegiesser and Günther (2014)		*		*	*			*			*		Automotive
Kannegiesser and Günther (2014)		*		*	*			*			*		Automotive

solve the MILP model. The model assisted decision makers in allocating appropriate number of contracts between different suppliers and 3PRL providers.

Carbon trading is a burgeoning industry. To emphasize the impact of carbon trading, Diabat et al. (2013) proposed a carbon-sensitive closed-loop supply chain (CSCLSC) model. The model minimizes carbon emission costs which is a major concern for large companies. It also reduces transportation and fixed facility location costs. Based on the carbon cap set by governing authorities, firms will incur costs if their current emissions are exceeding the carbon cap and will get monetary benefits if their emissions are below the carbon cap. The authors found that the emissions in a supply chain are linked to the level of sustainability adopted by raw material suppliers. If the raw materials are obtained from suppliers who emit excessive carbon emissions, then remanufacturing is beneficial to the supply chain. On the other hand, if the raw material supplier takes environmentally sound decisions and emits less emission then the manufacturer has a product which ultimately has a smaller environmental footprint and the manufacturer may not be interested in remanufacturing. Carbon price increase and the level of remanufacturing are interlinked. So governments must make suitable provisions to helps enhance product recovery efforts.

Fareeduddin et al. (2015) used a numerical experiment and found that the carbon cap and carbon cap-and-trade policies are competent to reduce emissions without increasing the financial burden on organizations. Though the carbon tax policy is highly flexible, it was found to impose a financial burden on enterprises to achieve a set emission standard as compared to the other policies.

Juhong et al. (2013) analyzed four pricing strategies for a CLSC. Based on the premium and penalty mechanism the four pricing strategies are: 1) government neither imposes a carbon tax on the manufacturer nor provides subsidies to the third-party representative 2) government imposes a carbon tax on manufacturers 3) government provides a subsidy to the third-party representative 4) government imposes a carbon tax on the manufacturer as well as provides a subsidy to the third-party representative. These strategies were examined using a Stackelberg game. Based on the results obtained the authors conclude that the government should provide subsidies to the remanufacturer and also impose a carbon tax on the manufacturer. Multiple benefits are derived from this strategy such as reduction in carbon emissions, improvement in the recycling rate and higher profits generated by the CLSC members.

Tao et al. (2015) considered a CLSC network where homogeneous products were manufactured in a multi period scenario. Two types of carbon emission constraints, namely periodic and global, were imposed on the manufacturers. The network equilibrium model was created using variational inequality and complement theory. Modified projection contraction algorithm was used to solve the process in MATLAB. Numerical examples examining the effect of periodic carbon emission constraints and examples examining the effect of global carbon emission constraints were solved. It was found that the global carbon emission policy was more beneficial to an organization as it allowed manufacturers to adjust the volume of its product portfolio over an entire planning horizon. But if the carbon emissions permitted under the global emission policy is limited then manufacturers would benefit from the periodic emissions policy if they are unable to adjust production volumes. Hence policy makers should enforce the right policy based on their goal of emission reduction.

In Xu et al. (2015) the Ministry of Environmental Protection (MEP) supported sustainable development by imposing penalties on manufacturers for violating emission standards and offering premiums to recycling centres to recover more products. The article developed a CLSC network equilibrium framework consisting of environmental factors. The framework was developed by integrating variational inequality theory and policies of the MEP. The optimal behaviour for achieving maximum profit for various members of the supply chain is described based on the upper limits of emission and lower limits of incentives for used goods.

We now study articles considering only the carbon tax emission policy.

Kannegiesser and Günther (2014) created a strategic sustainability optimization framework to guide policy makers in determining suitable regulations for increasing sustainability of different industries. Keeping economic and ecological objectives at the forefront, the article developed a mathematical model which is flexible to accommodate a variety of sustainability indicators, a variety of sustainability optimization strategies and other industry specific concerns. The value chain model consists of three submodels: process model, transportation model and product-in-use model. The process model is used to portray the various production and logistics activities between different members. Transportation activities is modeled using the Transportation model and sustainability issues are modeled using the Product-in-use-model. The product-in-use model is unique as it sheds light on the impact of making versus using a product from a sustainability standpoint. Three optimization strategies of 1) purely optimizing financial performance 2) optimizing the trade-off between sustainability indicators 3) minimizing the time to achieve sustainability was discussed.

In the second part of this paper Kannegiesser, Günther, and Gylfason (2014), the proposed model was applied to the automotive industry in Europe. It was found that the automotive industry shows great promise for sustainability improvement. The optimization model created an impact on the total emissions and costs related to the industry, proposed for relocation of production capacities, changes in transportation modes and considered electric vehicles for reducing emissions.

In this subsection we focus on the articles implementing the carbon cap and trade policy. Table 2.12 summarizes the articles described below.

Abdallah et al. (2012) combined location theory, inventory theory and reverse logistics theory to develop an uncapacitated closed-loop location inventory model. The MINLP displayed the interrelationship between the location inventory decisions in the forward and reverse paths. To enhance recovery efforts by OEMs the authors proposed a system of carbon trading. Companies which are forced to recover low value products at higher quantities could incur great losses. But on the other hand, companies which recover high value products may be at advantaged. A flexible policy making framework was introduced in the paper which provided carbon credits to OEMs that incur losses when products are recovered and reduced carbon credits for OEMs who do not

Table 2.12: Carbon emission based papers summary (carbon cap and trade policy)

Citation	Carbon emissions measured during									Carbon policy used			**Industry**
	Manufacturing of raw material/sourcing	Manufacturing of final/recyclable product	Product storage and handling	Sales and product usage	Energy mix used/power consumption	Remanufacturing/Recycling/Recovery	EOL/Disposing product/landfilling	Transportation (Forward/Reverse)	Total Emissions for the CLSC	Carbon cap	Carbon tax	Carbon Cap and trade and other policies	
Abdallah, Diabat, and Simchi-Levi (2012)												*	
Chaabane, Ramudhin, and Paquet (2012)		*				*		*				*	Aluminium production
Fahimnia, Sarkis, Dehghanian, Banihashemi, and Rahman (2013)		*				*		*				*	Company providing fibrous material used in car seats, carriers, sofas, dining chairs, filling material, and seat covers.
Zhou, Zhang, Liu, and Zhang (2011)									*			*	

recover products in sufficient quantities.

Chaabane et al. (2012) designed a sustainable supply chain by considering both material balance constraints and life cycle assessment principles. The model differentiates between solid, liquid and gaseous emissions developed in various processes. To abide by regulations on the maximum amount of GHG emitted and the minimum number of products recycled, the model considered emission trading scheme (ETS). A study in the aluminium industry is conducted to find the trade-off between economic and environmental goals under different cost and operational scenarios. The authors suggest for strengthening regulations like the ETS on a global scale and push for better carbon management policies for achieving cost-effective sustainable supply chains.

Fahimnia et al. (2013) created a CLSC model where carbon emissions are represented using dollar carbon cost. The focus of the article was to solve a bi-criteria model that aimed to reduce the environmental and economic impact of a CLSC. As carbon emissions are expressed in terms of a dollar value the two objectives can be combined in to a single objective function. They study a company which is going to be affected by a recently introduced carbon pricing scheme. Companies have to be ready to make strategic changes in response to the proposed carbon pricing initiatives. The supply chain costs and environmental impacts vary as the carbon prices changes. It is found that government subsidies promote supply chain decarbonization activities.

Zhou et al. (2011) proposed a two echelon CLSC consisting of a single manufacturer and retailer to understand the impact of various CLSC structures on the motive to collect used products and on the supply chain profits. The paper also analyzed the carbon emission reduction effects of the CLSC and the performance of the supply chain in the forward direction, reverse direction and the effect of government recycling subsidies. The paper proposed a framework to assist policy makers in achieving the optimal recycling subsidy model.

In this subsection we focus on the articles which do not implement a carbon reduction policy but have considered emissions at various stages of the CLSC. Table

Table 2.13: Carbon emission based papers summary (absence of carbon policy)

Citation	Carbon emissions measured during									Carbon policy used			Industry
	Manufacturing of raw material/sourcing	Manufacturing of final/recyclable product	Product storage and handling	Sales and product usage	Energy mix used/power consumption	Remanufacturing/Recycling/Recovery	EOL/Disposing product/landfilling	Transportation (Forward/Reverse)	Total Emissions for the CLSC	Carbon cap	Carbon tax	Carbon Cap and trade and other policies	
Das and Posinasetti (2015)	*	*	*			*		*					
Garg, Kannan, Diabat, and Jha (2015)								*					Geyser manufacturing
He, Xiong, and Lin (2016)		*		*		*	*						Traditional retailers and online e-tailers
Li, Guo, and Lan (2015b)	*	*		*	*	*			*				
Tiwari, Chang, Tiwari, and Kandhway (2016)	*	*				*	*	*					Semiconductor industries
Wang, Lu, Gao, Zhang, and Chen (2012)		*				*		*					Refrigerators
Chen, Wang, Chen, Wang, and Cheng (2014)		*				*		*					Solar energy

2.13 summarizes the articles describes below.
Das and Posinasetti (2015) worked on improving life cycle analysis (LCA) metrics in a CLSC planning model and the overall suppy chain profit. They proposed a model incorporating modular product design concept which assists in improving the processing times in manufacturing, remanufacturing, refurbishing, disassembly and repair of new or used products. The model discusses avenues for optimizing business performance, addresses concerns regarding harmful emissions and energy spent in industries. It achieves the above tasks by selecting alternative product designs and modules, optimizing the distribution routes and creating agreements with suppliers who follow environmentally friendly manufacturing processes. A supply chain in the welding industry consisting of multiple products manufactured in multiple plants and sent to multiple distribution centres and retail locations was studied. The model developed was solved using bi-objective Pareto optima solution approach and goal programming with weighted deficiency variables approach. The results of the case study gave an insight into the trade-off between profit, spent energy and harmful emissions produced.

Garg et al. (2015) developed a CLSC for an electrical appliance manufacturer. The manufacturer uses 3PL in the forward path and own trucks in the reverse path. A bi-objective model was formulated to minimize the number of vehicles utilized (for minimizing carbon emissions) and maximize the profits generated by the firm. The authors proposed an interactive multi- objective programming approach algorithm to solve the problem. It was found that the two objectives were conflicting. A solution which is environmentally strong supported hiring fewer trucks with a larger capacity and resulted in lower profits due to higher rental fee for trucks. A solution supporting greater profits resulted in hiring a larger number of trucks. Thus generating more emissions. A Pareto optimal curve was generated which will give decision makers an insight into the trade-off between the number of trucks hired and the profit generated.

Consumer free riding behaviour involves purchasing a product online at a lower price after visiting a traditional retail store to get a feel for the product. Consumer free riding behaviour has an impact on the carbon emissions produced during a products life cycle. He et al. (2016) dealt with the additional emissions caused due to consumer free riding behaviour in a dual channel CLSC and also found the consequence of imposing an e-commerce tax on emissions. E-commerce tax was found to be effective in curbing online trading and the carbon emissions generated.

To portray trade in today′s World, Li et al. (2015b) introduced a dual channel CLSC network with multiple entities present at the supplier level, manufacturer stage, retailer stage, demand markets level and recycling centre level. This paper also studied the conversion rate of raw materials, the conversion rate of worn-out products and the remanufacturing rate set by the government. It aimed to maximize profit and minimize carbon emissions for the whole supply chain. Utilizing Lagrange duality theory and variational inequality theory the decision-making behaviour of the various entities of the system was analyzed and equilibrium conditions for the supplier, manufacturer, retailer, need markets, recycling centres and carbon emissions was discussed. The equilibrium pattern of the dual CLSC is established and is solved using modified projection algorithm.

Tiwari et al. (2016) created a CLSC model for the semiconductor industry. Two objectives of maximizing profits and minimizing carbon emissions are dealt with simultaneously. Meta-heuristics are used to solve the NP hard problem. A new approach called Estimation of Distribution based Territory Defining Evolutionary Algorithm (EDATDEA) was used to solve 9 test problems and the results have been compared with the established Non-Dominated Sorting Genetic Algorithm II (NSGA II). EDATDEA is believed to be better than NSGA II based on the results from the test problems and the authors foresee its application in real life scenarios.

Wang et al. (2012) evaluated the trade-off between economic gains and ecological gains in a remanufacturing CLSC. A multi objective MILP model to determine the optimal location of facilities in a CLSC and the flow quantities between the members was developed for a low-carbon economy. Two optimization goals of 1) minimizing the total cost to the CLSC 2) minimizing environmental impact were considered. A

Table 2.14: Carbon emission based papers summary

Citation	Carbon emissions measured during									Carbon policy used		
	Manufacturing of raw material/sourcing	Manufacturing of final/recyclable product	Product storage and handling	Sales and product usage	Energy mix used/power consumption	Remanufacturing/Recycling/Recovery	EOL/Disposing product/landfilling	Transportation (Forward/Reverse)	Total Emissions for the CLSC	Carbon cap	Carbon tax	Carbon Cap and trade and other policies
No. of articles	5	14	3	4	4	10	2	12	5	7	5	7
% of total article	25	70	15	20	20	50	10	60	25	35	25	35

numerical study from the refrigeration industry was discussed and an iterative algorithm was designed to achieve the Pareto sets of the model. It was found that there is a trade-off between carbon emissions and waste generated along with a trade-off between the waste generated and the economic costs.

Chen et al. (2014) worked on a making the solar energy industry eco-friendlier by developing a CLSC for solar cells. The EOL solar products are assessed for quality. Good quality products are added to the forward logistics path after reproduction. Lower quality products are stripped of their working modules and remaining components are either reduced to basic raw materials or disposed. A deterministic multi-objective mixed integer programming model to minimize the CLSC cost and carbon emissions generated was developed. A multi-objective particle swarm optimization (PSO) technique with ideal-point non dominated sorting mechanism was used to obtain the optimal solution. For complex problems, PSO solutions were found to be more efficient and optimal compared to solutions generated by CPLEX.

Summary of carbon emission and CLSC articles

Research focuses on reducing emissions at all stages of the CLSC (supplier, manufacturer, recyclers and during transportation). Objectives of maximizing profits and minimizing carbon emissions, number of transportation vehicles, CLSC costs, and time to achieve sustainability have been tackled. Carbon trading, carbon pricing strategies in CLSCs, consumer free riding behaviour, e-commerce tax, government recycling subsidies, emission policies such as carbon cap, carbon tax, carbon cap-and-trade were studied.

Examples and cases studies from the solar energy industry, semiconductor manufacturing, electrical appliance manufacturing, retail sector, refrigeration industry, personal computer industry, welding and printer manufacturing were elaborated in this multifarious research.

From the summary Table 2.14, emissions from manufacturing of the final /recyclable product, and from transportation, remanufacturing, recycling, recovery of products has been extensively covered by scholars. Future works could focus on the emissions generated during product storage and handling, from sales and product usage, emissions based on the type energy consumed and emissions from disposal activities. As these categories received less coverage. Around 35 % of articles did not consider carbon emission policies in their research but it would be interesting to include the new policies and regulations developed by governments the world over to restrict carbon emissions.

This section presented a brief review on CLSC models with carbon emission considerations. The next section reviews greenness indices developed to evalute the performance of CLSCs.

2.8 Greenness index

GSCM assists consumers and industries to reduce their environmental impact. Performance assessment of the green supply chain is critical but it becomes increasingly challenging due to the closed-loop nature of the supply chain. There should be a scientific and standardized evaluation index system which evaluates all aspects of the supply chain while amalgamating financial and non-financial indices. If corporations can measure how environmentally friendly different supply chain alternatives are then they can select the eco-friendliest alternative. The Greenness index is a tool which assists organizations during the performance evaluation of supply chain alternatives. The following papers propose a variety of methods to a develop a greenness index. Papers are grouped according to the method used to develop the index system.

We first study the variety of criteria used by different authors to rate supply chains in Table 2.16 and 2.17

From the summary Table 2.18 we see that supply chains have been rated across all critical steps from the design stage to the products EOL. Process such as recycling and remanufacturing along with social impacts of manufacturing organizations are given special importance. Most authors included environmental and economical criteria but very few authors have included strategy formulation, relationship between entities, political and regulatory attributes in their index system. We now study the papers in detail.

From the summary Table 2.21 we can see that authors have predominantly used fuzzy methods followed by Analytic Hierarchy Process (AHP) and other techniques in developing the greenness index. We first study the fuzzy methods based index systems. Fuzzy multi-attribute decision making approach, fuzzy comprehensive evaluation method and fuzzy analytic hierarchy process (F-AHP) are the principal fuzzy methodologies used to develop the greenness index system.

Cao et al. (2011) reviewed the greenness level of a closed-loop supply chain for the fresh food industry. The fresh food industry deals with dairy products, vegetables, fruits, meat and aquatic products consumed by people on a daily basis. As fresh food is highly perishable it is imperative to study its green supply chain to ensure the quality of products. The index considers planning, sourcing, cultivation/breeding, processing, delivery and returns of products. The problem is multi-index and multi-level which required the evaluation of qualitative and quantitative criteria simultaneously. The authors developed a Fuzzy-AHP-Grey evaluation model. This model combines fuzzy comprehensive evaluation method, analytical hierarchy process and the grey evaluation method to assess the green degree of fresh food supply chains.

Ferreira et al. (2012) developed a supply chain assessment model which combines 4 qualities of being agile, lean, resilient and green. To create the Lean, Agile, Resilient

Table 2.15: criteria for evaluating supply chains - 1

Citation	**criteria to evaluate the supply chain**														
	Design and Planning	**Manufacturing**	**Purchasing, packaging and inventory control**	**Business process and operational flexibility**	**Forward and reverse logistics**	**Returns**	**Reuse/recycle/remanufacturing/refurbishing**	**Waste disposal**	**Environmental and Pollution**	**Economical (cost and profit)**	**Social attributes & customer satisfaction**	**Information value & sharing**	**Innovation/Technology/Certifications**	**Strategy formulation & nodes relationship**	**Political & regulatory attributes**
Cao, Xia, Cao, and Wang (2011)	*	*	*		*	*									
Ferreira, Azevedo, and Fazendeiro (2012)	*		*		*		*		*				*	*	
Gan and Yu (2009)							*		*	*	*	*			
Gopal and Thakkar (2015)								*	*	*	*		*		*
Jun (2009)	*	*		*	*	*	*		*	*	*	*			
Li and Wang (2010)							*		*	*	*				
Liang, Gui, Fei, Hong, and Dong (2011)									*	*					
Lin (2013)	*	*	*				*		*	*				*	*
Liu and Wang (2011)							*	*	*	*	*				
Meng and Zhang (2008)	*						*		*		*		*		

Table 2.16: criteria for evaluating supply chains - 2

Citation	**criteria to evaluate the supply chain**														
	Design and Planning	**Manufacturing**	**Purchasing, packaging and inventory control**	**Business process and operational flexibility**	**Forward and reverse logistics**	**Returns**	**Reuse/recycle/remanufacturing/refurbishing**	**Waste disposal**	**Environmental and Pollution**	**Economical (cost and profit)**	**Social attributes & customer satisfaction**	**Information value & sharing**	**Innovation/Technology/Certifications**	**Strategy formulation & nodes relationship**	**Political & regulatory attributes**
Pang, Hu, and Li (2011)		*		*			*		*	*	*		*		
Tseng, Lim, and Wong (2015)	*		*	*			*	*	*	*	*	*	*	*	
Wenhai, Peifang, Dianli, and Bin (2009)							*		*	*	*	*		*	
Wibowo (2013)	*	*	*	*											
Xiangru and Wei (2009)							*		*	*	*		*		
Yang, Zang, and Hao (2009)				*	*		*	*	*	*	*	*	*		
Zhang et al. (2005)				*					*	*	*	*			
Zhang (2014)				*		*			*	*	*		*		
Zheng (2010)								*	*	*	*				

Table 2.17: criteria for evaluating supply chains - 3

Citation	**criteria to evaluate the supply chain**														
	Design and Planning	**Manufacturing**	**Purchasing, packaging and inventory control**	**Business process and operational flexibility**	**Forward and reverse logistics**	**Returns**	**Reuse/recycle/remanufacturing/refurbishing**	**Waste disposal**	**Environmental and Pollution**	**Economical (cost and profit)**	**Social attributes & customer satisfaction**	**Information value & sharing**	**Innovation/Technology/Certifications**	**Strategy formulation & nodes relationship**	**Political & regulatory attributes**
Chen, Weng, and Zhao (2009)				*			*		*	*	*				
Nie (2016)						*	*		*	*	*			*	
Sellitto, Borchardt, Pereira, and Silva (2013)	*	*	*	*	*		*	*	*				*	*	
Sellitto, Bittencourt, and Reckziegel (2015)	*	*	*	*	*		*	*	*				*	*	
Genchev, Glenn Richey, and Gabler (2011)					*	*	*	*		*	*	*			
Hervani, Helms, and Sarkis (2005)		*	*			*	*	*	*	*	*				*
Yao and Zhang (2011)				*			*		*	*	*	*	*		
Sarkis (2003)	*	*	*	*	*		*	*	*	*			*		
Gao, Li, and Song (2009)					*	*	*		*	*	*	*			
Feng, Sifeng, Lijun, Weizhao, and Zhengyang (2013)				*			*	*	*	*	*	*	*		
Xue (2010)	*			*		*		*	*	*	*				

Table 2.18: Summary table - criteria for evaluating supply chains

Citation	**criteria to evaluate the supply chain**														
	Design and Planning	**Manufacturing**	**Purchasing, packaging and inventory control**	**Business process and operational flexibility**	**Forward and reverse logistics**	**Returns**	**Reuse/recycle/remanufacturing/refurbishing**	**Waste disposal**	**Environmental and Pollution**	**Economical (cost and profit)**	**Social attributes & customer satisfaction**	**Information value & sharing**	**Innovation/Technology/Certifications**	**Strategy formulation & nodes relationship**	**Political & regulatory attributes**
Total articles	11	9	9	14	9	8	22	12	27	24	22	10	13	7	3
% of all articles	37	30	30	46.7	30	27	73.3	40	90	80	73.3	33.3	43.3	23.3	10

and Green (LARG) index, the authors used fuzzy logic. The paper has a twofold objective of creating a supply chain evaluation system which will help in achieving quality improvements and assist decision makers to accommodate policy changes in supply chain performance measurement.

Green strength of a RL system is said to be high when the logistics system is environmentally friendly. Gan and Yu (2009) created an evaluation system for finding the green strength of the RL system. The green strength of the RL system is found using quantitative analysis whereas the environmental impact of the RL is estimated qualitatively. The paper makes use of a two-level comprehensive fuzzy evaluating model utilizing indexes relating to the environmental character, economic character, resource character, technical character and social character. The green strength for a household electrical appliance manufacturer was studied. It was found that the company showed poor performance on social and environmental attributes.

Gopal and Thakkar (2015) developed a composite performance index to evaluate the sustainability of the automobile industry supply chain. The model unifies

Table 2.19: Greenness index - Fuzzy methods focus

Citation	**Aggregate Methods**								**Industry Examples**
	Fuzzy methods	**Analytic hierarchy process (AHP)**	**Delphi method**	**Grey relational analysis**	**Qualitative research methodology**	**Balanced score card**	**Analytical network process**	**Other**	
Cao et al. (2011)	*	*		*					Produce (Fresh food)
Ferreira et al. (2012)	*								Automotive
Gan and Yu (2009)	*								Household electrical appliance manufacturer
Gopal and Thakkar (2015)	*							Liberatore score and signal to noise ratio	Automotive
Jun (2009)	*	*	*						
Li and Wang (2010)	*								Air conditioning
Liang et al. (2011)	*	*							Construction
Lin (2013)	*							Decision making trial and evaluation laboratory method	
Liu and Wang (2011)	*	*							Automotive
Meng and Zhang (2008)	*								
Pang et al. (2011)	*								Iron and steel
Tseng et al. (2015)	*		*			*	*		Printed circuit board (PCB)
Wenhai et al. (2009)	*			*					
Wibowo (2013)	*								
Xiangru and Wei (2009)	*								Automotive
Yang et al. (2009)	*	*				*			
Zhang et al. (2005)	*								
Zhang (2014)	*								
Zheng (2010)	*		*						

Table 2.20: Greenness index - Other methods

Citation	Aggregate Methods								Industry Examples
	Fuzzy methods	Analytic hierarchy process (AHP)	Delphi method	Grey relational analysis	Qualitative research methodology	Balanced score card	Analytical network process	Other	
Chen et al. (2009)		*		*				Information entropy method	Electronics
Nie (2016)		*	*						
Sellitto et al. (2013)		*			*				Footwear
Sellitto et al. (2015)		*						Five point Likert scale	Automotive
Genchev et al. (2011)					*				Electronics and other industries
Hervani et al. (2005)					*				
Yao and Zhang (2011)						*			
Sarkis (2003)							*		
Gao et al. (2009)								Membership conversion algorithm	
Feng et al. (2013)								Meta analysis	
Xue (2010)								Data envelopment analysis (DEA)	

Table 2.21: Summary table for greenness index methods

Citation	**Aggregate Methods**							
	Fuzzy methods	**Analytic hierarchy process (AHP)**	**Delphi method**	**Grey relational analysis**	**Qualitative research methodology**	**Balanced score card**	**Analytical network process**	**Other**
Total articles	20	9	4	3	3	3	2	7
% of all articles	67	30	13	10	10	10	7	23

multiple sustainability indicators. It also combined qualitative and quantitative approaches while developing the supply chain sustainability performance index. The article focused on sustainability indicators associated with economic, environmental, social, technical and political aspects of the supply chain. The weights of the indicators are determined using fuzzy analytical hierarchy process (FAHP). Qualitative indexes are determined using Liberatore score method while quantitative indexes are determined using signal to noise (S/N) ratio method. Liberatore score method is used as it can evaluate indicators based on past performance on a linguistic rating system. As we look at either the maximum or minimum values of indicators, the authors implemented smaller the better and larger the better S/N ratio. Finally, a composite sustainable supply chain performance index was developed and a case study from the Indian automotive industry is used to represent the workings of the model.

Jun (2009) proposed a performance evaluation model for cluster green supply chain. The model is based on circular economy. Cluster green supply chain stresses on the need to consider an enterprises environmental effects apart from purely optimizing the procurement, production and distribution activities. The authors studied a case in the industry to present the models effectiveness. Weights in the case study were determined using a combination of Delphi method and AHP. The authors expatiated on performance management and control strategies for cluster green supply chains.

Li and Wang (2010) presented an evaluation index system which included resource properties, energy properties, environment properties, economic attributes and social attributes. The index system was developed using related literature, ISO 14000 environment system requirements and the factors influencing a supply chain in a manufacturing environment. The main criteria are further subdivided into multiple sub criteria. Fuzzy comprehensive evaluation technique was used to evaluate the greenness of the supply chain. An air-condition manufacturing enterprise which follows green supply chain practices in manufacturing household and central air-conditioning systems was studied. It was found that the companys performance on the energy, environment and economic front was good but the resource attributes and social attributes could be improved.

The construction industry though aware of its responsibilities towards conservation of raw materials, energy and the environment, the industry fails in achieving its conservation targets. Hence Liang et al. (2011) presented a model for green evaluation of a construction supply chain. Resource saving, pollution reduction and economic attributes are the main factors to be evaluated in a construction supply chain. The evaluation model is solved using a combination of AHP and fuzzy comprehensive evaluation technique.

Lin (2013) studied the main influential factors affecting GSCM practices. To create a model to find the cause and effect relationship between criterion the authors employed a combination of fuzzy set theory along with decision making trial and evaluation laboratory (DEMATEL) method. The combination of techniques overcomes the limitation of less input data and vagueness of human judgment. GSCM practices such as purchasing, design, customer and supplier collaboration, product recovery and reuse of products, environmental performance, economic performance, regulations and pressure from stakeholders was discussed in detail.

Liu and Wang (2011)developed 8 primary indices and 23 secondary indices in a AHP and fuzzy comprehensive evaluation model. The 8 primary indices used were: pollution to the environment, energy utilization rate, output and treatment, waste resource utilization rate, staff environmental awareness, the cost of each link, enterprise received benefits and customer satisfaction. A major automotive parts manufacturing company was assessed for its greenness. The authors suggested enhancing the training of company staff, improving after sales service, inclusion of environmental scientists during product design stage and other suggestions to improve the greenness of the company.

The need and significance of pursuing green supply chain management in Chinese enterprises was discussed in Meng and Zhang (2008). The paper used Delphi technique, AHP and fuzzy comprehensive evaluation method to create the evaluation model. 6 primary indicators and 19 secondary indicators are used in the model. Primary indicators focus on the green degree of the products, level of clean production, waste emission levels, resource and energy levels, level of environmental management and green culture of the enterprise. A study on a motorcycle manufacturing organization was conducted by a panel of 12 experts. The company achieved an overall score higher than that of the industry average. The authors suggest that if the environmental management standards of supply chain partners are increased then there is a great probability for the company to achieve higher greenness scores.

Pang et al. (2011) proposed a green supply chain evaluation model for the iron and steel industry. The iron and steel industry is one of the major industries in China's economic development. It is major consumer of energy, resources and a source of excessive pollution. Green purchasing, green manufacturing, green marketing and waste recycling are the main indicators in the green supply chain evaluation model. The evaluation index system also considers criteria like green initiative, cost value, process, customer service, talent and development. Fuzzy Analytic Hierarchy Process (FAHP) was used in the assessment of the model. The green supply chain scored between average to above average in the performance evaluation model.

Tseng et al. (2015) proposed a model to measure the sustainable supply chain management (SSCM) performance. The paper aims to evaluate the supply chain on sustainability, internal business processes, stakeholder value, learning and growth. The Balanced score card (BSC) model assists decision makers in converting linguistic expressions into crisp values. The performance evaluation indicators depend on each other and are based on subjective opinions. To overcome these characteristics of the indicators, the authors used a combination of Fuzzy Delphi Method (FDM) and ANP to create a quantitative evaluation model. The paper considered a case of a leading printed circuit board (PCB) manufacturer. The paper has dual benefits of enabling stakeholders to understand network hierarchical relationships as well as improve the performance and management effectiveness of sustainable supply chains.

Wenhai et al. (2009) selected customer service, degree of information sharing, supply chain management cost, relationship between node enterprises and green environmental protection as the critical factors to evaluate the green supply chain. The critical factors are further sub-divided into 25 second grade indexes. Using fuzzy comprehensive evaluation technique, the performance evaluation of the whole supply chain was conducted. Grey incidence analysis method was used to compare the goal supply chain with the benchmark supply chain.

Wibowo (2013) created a grading system which evaluates qualitative attributes of supply chain alternatives based on human subjectivity. Many conflicting criteria make the problem more complex and hence a fuzzy multi-attribute decision making procedure was adopted. The key attributes of green design, green manufacturing, green purchasing and green marketing was used to assess supply chain alternatives.The decision maker uses 5 linguistic variables for subjective assessment of qualitative measures and attribute weights. 9 triangular fuzzy numbers are then used to represent the linguistic variables. To show the efficacy of the proposed approach, 5 supply chain alternatives are assessed and one of the alternatives was found to be superior to the others as it has a higher performance index

Xiangru and Wei (2009) created an assessment system for the reverse supply chain in the automotive industry. The evaluation index system depends on factors related to the environment, economic attributes, resource utilization, technological attributes and social attributes. The paper elaborated on the dismantling and recovery process of scrapped automobiles. Considering the uncertainty involved in the green degree evaluation index, 4 grades (very good, good, general and poor) for evaluation are present and the authors used fuzzy comprehensive evaluation method. Power value factor judgment was applied to find the weights of the assessment indexes. From the case study it was found that the supply chain lags on the resource attributes and environmental attributes front. By reducing solid waste and water pollution along with increasing utilization rate of recycled materials and recovered products the automotive reverse supply chain would have a smaller environmental footprint

Yang et al. (2009) implemented Balanced score card (BSC) sorting method to evaluate the performance of the reverse supply chain. Reverse supply chains are evaluated to find areas of improvement in resource utilization, flexibility, reduction of response time and reduction of cost to the company. The first degree indexes are related to financing, customer service, internal operations, developing innovations and the environment. To simplify complicated analysis into a sequential hierarchical structure and to integrate qualitative and quantitative analysis, AHP is used. Triangular fuzzy numbers assist AHP to analyze the fuzziness of experts judgement.

Zhang et al. (2005) proposed the following criterions for the assessment of the green supply chain: financial value, environmental protection, information value, customer service, cost and operational flexibility. Utilizing fuzzy assessment method, the model was evaluated. A CLSC consisting of a component manufacturer, producer, transporter, vendor, service centres, customers, recycler and material manufacturer was studied.

The index system proposed by Zhang (2014) was constructed based on suggestions from experts, statistics and surveying the supply chain. Economic profit, environmental protection, business process, customer service and sustainable development were the evaluation indexes in this model. The fuzzy analysis method of multi attribute decision making helped to create a quantitative evaluation index system. The model and algorithm was tested by evaluating the green supply chain of 3 companies from a particular industry.

Zheng (2010) developed an index system based on the Delphi Method to represent the environmentally amicable conditions of a supply chain in manufacturing. Several environmental factors cannot be evaluated using statistical techniques and are judged by words like good and bad. To deal with subjectivity involved in decision making, Fuzzy comprehensive evaluation method was used. Whereas AHP provided an objective and quantitative analysis of the situation. Hence a combination of F-AHP combines the benefits of both worlds to evaluate environmental factors. Major attributes evaluated were related to the environment, energy, society, resources and economic attributes.

From reviewing the above articles we see that nearly half the articles use an additional method along with fuzzy concepts. We now study articles using AHP method to create the index system.
Cao et al. (2011), Jun (2009), Liang et al. (2011), Liu and Wang (2011) and Yang et al. (2009) have used AHP with fuzzy concepts. The following articles have developed the index system using AHP and techniques apart from fuzzy logic.

The indexes in Chen et al. (2009) are related to financial performance, customer service level, cost level, business process and environmental performance. To determine the weight of each index the authors used a combination of AHP and information entropy method. Information entropy focuses on objective information in the data whereas AHP deals with subjective information. The supply chain performance evaluation model is based on grey system evaluation and it is tested on four green supply chains from the electronics industry.

Nie (2016) created an evaluation index system based on three layers: environmental impact degree, resource utilization rate, environmental benefit and reputation.

Expert opinion was used for determining the relative importance of indicators and a combination of Delphi method and AHP was used to assign weights to the different indicators. The index system was developed to follow importance principles, dynamic principles, comparability principles, quantitative principles and economic principles. Four qualitative opinions like very good = 1, good = 0.8, general = 0.6 and poor = 0.4 were used by experts to rate the indexes. The ability to incorporate real-time evaluation and analysis is one of the innovations of this paper.

Sellitto et al. (2013) proposed a qualitative model for green performance assessment of the supply chain. The model consists of three indicators: strategy, innovation and operations. The indicators are ranked based on five degrees: very good = 1, good = 0.75, neutral = 0.5, bad = 0.25, very bad = 0. An example from the footwear industry was used to test the model. It was found that the footwear company was performing only at 40 % of its capabilities in regard to GSCM. Operations was found to be the worst performing indicator and efforts to improve manufacturing, reverse logistics, distribution and disposal would enhance the overall performance of the supply chain

Sellitto et al. (2015) focused on evaluating the degree of implementation of GSCM in industrial supply chains. A four-echelon supply chain of a company manufacturing tractors and engines, and an electric auto part manufacturer was evaluated using the proposed model. A qualitative model composed of 3 constructs relating to strategy, innovation and operations was created. The 3 constructs are further categorized into 16 variables and are ranked by managers of the company using the five point Likert scale (1 = very high, 0.75 = high, 0.5 = fair, 0.25 = weak, 0 = null). Results from the focal companies were integrated by an importance vector obtained from AHP and an overall index to measure the implementation of GSCM was created. Both focal companies achieved a score greater than 70 %. The authors suggest that the tractor and engine manufacturer focus their efforts on improving green strategic processes while the electric auto part manufacturer should focus on improving their green innovation process.

Delphi method was used by the following authors in the development of the greenness index system: Jun (2009), Tseng et al. (2015), Zheng (2010) and Nie (2016). While Grey relational analysis was used by Cao et al. (2011), Wenhai et al. (2009) and Chen et al. (2009).
Qualitative research methodology was also used by scholars. Apart from Sellitto et al. (2013), Genchev et al. (2011) and Hervani et al. (2005) have also used a qualitative research methodology.

Genchev et al. (2011) worked on a methodology to formalize the RL process. By formalizing their RL processes, companies can control the value-added to the supply chain. They studied the best-in-class RL programs and developed a flow charting technique to assess currently implemented RL programs and provide improvement suggestions. The assessment tool is based on qualitative research methodology, semi-structured interviews and site visits. Six RL processes like return initiation, type of routing, returns receiving, disposition options (e.g. repair, refurbish, donate), claim settlement with supplier/customer, analyzing returns and measuring the performance of RL programs were studied in great detail. The assessment tool can help firms notify customers/suppliers on the time it would take to complete the returns process and credit them with the appropriate monetary value.

Hervani et al. (2005) proposed a green supply chain performance measurement system based on ISO guidelines. The paper combined supply chain, environmental and performance management into one frame work. The authors discussed 1) internal pressures like cost and profit, external pressures from regulatory authorities and competitors 2) measure and metrics from toxic releases inventory and Global Reporting Initiative 3) tools like AHP, balanced score card, data envelopment analysis. Considering both inter-organizational and environmental concerns in a business setting is one of the key additions made by this article.

Balanced scorecard was used to achieve a balance between a large number of indicators. The indicators may be short term and long term goals, financial and non-financial objectives, leading and lagging indicators or may be stock and flow indicators. Yao and Zhang (2011) used the balanced scorecard technique to develop a performance evaluation model to assess the green supply chain. The model considered indicators related to financial performance, customer service, internal operations, environmental operations along with learning and development. Balanced score card method was also used by Tseng et al. (2015) and Yang et al. (2009).

The external links that an organization has in its supply chain are critical for its success and hence Sarkis (2003) developed a strategic framework to evaluate alternatives which can aid decision makers. Alternatives such as who would be the best supply chain partner, which is a better technological advancement to be incorporated in the old system and what organizational policies to follow were tackled. Due to the uncertainties and complexity involved in strategic decision making, the authors have used Analytical Network Process to create a network hierarchy. ANP is a practical tool for multi-criteria strategic decision making and assists managers to dynamically incorporate interdependence among factors. One of the major drawback of ANP is the large amount of input data and complexity of sensitivity analysis. Tseng et al. (2015) also implemented ANP in their study.

We finally classify articles which have implemented a different methodology to develop the greenness index. Gopal and Thakkar (2015) used Liberatore score and signal to noise ratio; Lin (2013) used Decision making trial and evaluation laboratory method; Chen et al. (2009) used Information entropy method, whereas Sellitto et al. (2015) used Five point Likert scale in developing the greenness index. These article were discussed in detail in the above paragraphs.

The following articles also used a variety of methodologies to develop the greenness index.

Gao et al. (2009) discussed design, selection of materials and suppliers, production, logistics, packaging, marketing and recycling. The green nature of the different elements of a products life cycle are discussed to ensure that the final product is environmentally friendly. Based on the ISO 14000 environmental standards, traditional supply chain and green supply chain characteristics, five indices were created (customer satisfaction index, the degree of information sharing, level of logistics integration, node enterprises relations and green level). The paper used membership conversion algorithm to solve the proposed performance evaluation model.

Feng et al. (2013) used Guangxis manufacturing industry to propose a performance evaluation system for green supply chain management. The evaluation system is based on recycled economy. Recycled economy emphasizes the importance of efficient and cyclical utilization of resources. The authors used meta-analysis method to sum up the findings from key journals and came up with 6 level I indices and 24 level II indices.Green supply chain management was found to hold the key to improving Guangxis manufacturing industry.

Xue (2010) considered three key elements of customer value, supply chain value and environmental value for the evaluation system. Customer value is further categorized into flexibility, reliability, quality and price components. The paper introduced a Data envelopment analysis (DEA) model, considered two virtual Decision Making Units (DMUs) and introduced weights to calculate efficiency scores for these DMUs. A case study consisting of 6 supply chains are represented as 6 DMUs. These DMUs are analyzed by using DEA and the supply chains are ranked based on the efficiency score.

Summary of greenness index models

Models primarily evaluate supply chains from an economic, social and environmental stand point. Greenness index models are developed using fuzzy methods, AHP, Delphi method, grey relational analysis, balanced scorecard method, analytical network process, qualitative research methodologies and other techniques.

Evaluation of the supply chain involves combining parameters which have been evaluated subjectively with parameters which can be evaluated objectively. (F-AHP) is one of the main methodologies used to overcome subjectivity during the evaluation process. Some of the other methods used to solve proposed models are the membership conversion algorithm, AHP with information entropy method, AHP with uniform distribution and initial prioritization, Liberatore score and signal to noise ratio method.

Supply chains in the automotive industry, air conditioner manufacturing, construction industry, fresh food business, footwear industry, iron and steel manufacturing and electrical appliance manufacturing were evaluated. There has been a great emphasis on using fuzzy methodologies, authors can focus on using different methods such as preference function modeling (Barzilai, 2005) and other multicriteria aggregation function.

2.9 Future research

Based on the preceding literature review, the following future research opportunities were identified:

- For articles dealing with uncertainty using stochastic and robust programming.
    - Uncertainty in return quality, pricing and facility capacity can be studied in greater detail.
    - More than half the articles based on uncertainty use MILP as a modeling approach. Other modeling methods such as queueing, MINLP and heuristics should be given more importance.
    - Nearly all objective functions are single/bi objective aimed at either profit maximization or cost minimization. It will be beneficial for researchers to consider multi-objective functions with a different focus.
    - Automotive, iron and steel, and electronics industries has been covered extensively. Hence researchers should investigate applications in other industries.
- For return product quality and reliability based articles.
    - There has been a great focus on return product quality and grading but research on return product reliability is lacking. Hence a focus on return product reliability can provide decision makers a better understanding of the return product and help them in taking better decisions for remanufacturing/recycling operations.

  - To make mathematical models more representative of real world situations, models with multi components, multiple products and multiple periods can be investigated in detail.

- For carbon emission based articles.
  - Carbon emissions generated from sourcing raw materials, product storage, handling, usage, sales, emissions based on energy consumed and emissions from disposal activities can be covered in greater detail in future works. It would also be good to incorporate new carbon emission policies introduced by governments the world over.

- For greenness index based articles
  - Greenness indexes have been primarily developed using fuzzy methods and it would be interesting to see the use of other methodologies such as preference function modeling.
  - Future works in greenness index should increase the focus on information sharing and relationship between the different entities in the supply chain.
  - As incorporating political and regulatory policies in design of the supply chain is critical, it will be beneficial for researchers to give importance to this criteria during the creation of greenness indices.

2.10 Conclusion

In this article we developed a literature review focused on uncertainty, return product quality and reliability, carbon emissions and greenness index in CLSC and RL. The articles were classified according to uncertainty overcome, industry application, emission policy and similarity in settings/methods. We also provide a review of state-of-the art literature reviews articles in this field. Multiple future research opportunities have been put forth.

CHAPTER 3

MULTICOMPONENT MULTIPRODUCT CLSC DESIGN WITH TRANSSHIPMENT AND ECONOMIES OF SCALE

3.1 Introduction

A closed loop supply chain is a combination of the forward supply chain and the reverse supply chain. The reverse supply chain begins with product acquisition, and transportation of returns to processing centres where they are tested, sorted and reprocessed based on the most profitable reuse alternative (Guide, Harrison, and Van Wassenhove, 2003a). After remanufactured products are produced, they are sold in either primary markets at a discounted price or in secondary markets (Venkatadri et al., 2017). Recovering returned products generates economic, environmental, informational and consumer value (Schenkel et al., 2015) and hence it is encouraged by governments and pursued by entrepreneurs. This tremendous value generating opportunity has been studied by researchers and practitioners over the years and has resulted in the publication of many research papers. Given the large number of papers devoted to closed-loop supply chain management, it is not surprising to find a substantial number of literature reviews on the topic.

Govindan et al. (2015) reviewed 382 articles on RL and CLSC published between January 2007 and March 2013 and classified them based on the problem solved, type of work (surveys, case studies, etc.), deterministic or uncertain parameters, modeling approaches , solution methodologies, decision variables, number of periods, number of products and objective function employed.

Schenkel et al. (2015) classified 144 articles dealing with GSCM, RL, and CLSC. They discovered that value adding concepts such as partnerships and collaborations, product design features, service and organizational policies, IT solutions and supply chain processes create economic (cost reduction, revenue generation, risk reduction),

environmental (corporate image, green processes and products), informational and consumer value.
To shed light on quality, reliability, maintenance and warranty issues in the CLSC, Bhakthavatchalam, Diallo, Venkatadri, and Khatab (2015) reviewed 104 articles published after 1985 and classified them based on problem context and solution methodologies. One of the gaps identified in their paper is how the quality of recovered cores affect their reliability and how to efficiently screen or test EOL systems before and after acquisition.

Akçalı and Cetinkaya (2011) categorized inventory and production planning in the CLSC into deterministic and stochastic issues based on the modeling of consumer demand and returns. Deterministic models were further classified into constant, continuous time varying and discrete time-varying demand and return models while stochastic models are classified into continuous and periodic review models.
Govindan and Soleimani (2017) summarized 83 articles published in the Journal of Cleaner Production. The articles were grouped into evaluation studies, surveys, conceptual and mathematical frameworks, review studies, simulation, decision making, planning and product design studies. Qualitative studies were found to outnumber quantitative papers. A total of 69 out of 83 papers dealt with RL and the rest studied the CLSC.

Based on the classification provided by Akçalı, Çetinkaya, and Üster (2009) and on the literature review conducted in the previous chapter of this thesis, we conclude that most RL and CLSC articles focus on facility location, remanufacturing and transportation. Secondary areas of interest are in manufacturing, inventory management, disposal, collection of returns and demand satisfaction. It may be noted here that there has been little focus on fixed/linear capacity expansion and inspection, quality and reliability issues.
Other shortcomings identified in the current state of the art include the lack of consideration given to potential transshipment of cores between reprocessing centres and

the modeling of economies of scale. Large remanufacturing organizations with geographically dispersed facilities may experience more returns in some locations making the option of transferring cores to facilities in other regions viable. Jabbarzadeh, Haughton, and Khosrojerdi (2018) define lateral transshipment as a strategy to transport products from a facility with surplus to a facility facing shortages, which can assist in moving products more efficiently across the network thus preventing any shortages or surplus.

Economies of scale are common in many business operations. Under economies of scale the fixed cost to establish a facility and the variable cost to process products at the facility decreases as larger facilities are established. Due to economies of scale, mega stores such as Walmart and Costco generate huge savings and pass on the benefits to the consumers. Similar benefits can also be achieved in the case of RL and CLSC.

The goal of this paper is to propose a new CLSC design model incorporating economies of scale to locate IRDCs with transshipment of inspected products between IRDCs and reliability considerations. We will show the benefits of explicitly integrating these elements through several numerical experiments. The remainder of the paper is organized as follows. Section 3.2 contains a literature review on EOS, reliability and quality, and transshipment. Section 3.3 explains the framework of the CLSC network used in this paper and the proposed MILP model is formulated in section 3.4. Numerical examples analyzing the proposed model are provided in section 3.5. And finally, future work and conclusions are provided in section 3.6.

3.2 Literature review

In this section, a succinct review of five key papers is proposed for each of the following three areas: economies of scale, reliability/quality and transshipment.

3.2.1 Economies of scale

Due to uncertain supply and demand characteristics, manufacturers must carefully evaluate their options before establishing or increasing the capacity of their remanufacturing facilities in their network (Diaz and Marsillac, 2017). They may overcome this long-term capacity planning problem by establishing large facilities at high initial fixed costs to take advantage of economies of scale or establishing smaller facilities and having gradual increments in capacities (Georgiadis and Athanasiou, 2013).

EOS principles can be applied to the volume of products transported or collected from consumers, but is primarily applied to facility capacity (Vieira, Vieira, Gomes, Barbosa-Póvoa, and Sousa, 2015; Georgiadis and Athanasiou, 2013; Bucci, Woolard, Joines, Thoney, and King, 2014).

Vieira et al. (2015) included nonlinear dimensioning factors in the design of a CLSC and solved the model using ant colony optimization. In addition to EOS in facility capacity, EOS in transportation distance is integrated to their model using a tapering principle and EOS in transported quantities is expressed using a cost/transported quantity coefficient. Piecewise linearization techniques are used to model non-linear factors in an alternative MILP model.

Georgiadis and Athanasiou (2013) found that a flexible capacity planning model could overcome the uncertainty in consumer demand, sales pattern, return quantity and return timings. Solutions to a long-term capacity planning problem in the reverse loop of a CLSC is provided in this research. This work solves the dilemma that exists between establishing large facilities at high initial fixed costs to take advantage of economies of scale or establishing smaller facilities and making gradual increments to capacity. Using experiments from the electronics and automotive industry the authors show that a flexible capacity planning model is better than a model in the paper based on control theory. The proposed flexible policies also effectively deal with the excessive investment in remanufacturing facilities found in near-optimal policies.

Bucci et al. (2014) used a nonlinear model and heuristics developed for a forward supply chain to solve a facility location problem in the reverse logistic network domain. Impact of EOS on recycling facilities and collection volumes are studied. Data from Carpet America Recovery Effort (CARE) was used to test the proposed model and its results are compared to a network which increases the number of collection centres when greater quantities of carpets are to be recycled. The benefits of the proposed research over existing MILP models is that it provides near optimal solutions to problems, can work with a larger number of potential facilities and includes impacts of EOS on variable costs at facilities.

EOS is also applied to the volume of products collected from consumers and to the quantity of products to be remanufactured in Wu (2015) and Diaz and Marsillac (2017) respectively.

Wu (2015) developed a CLSC model with an OEM and a remanufacturer. Selling remanufactured products in the primary market creates price competition between OEMs and remanufacturers. Both OEMs and remanufacturers attract consumers to return their used products using incentives. The authors study the remanufacturers ability to overcome competition in the forward and reverse supply chain using EOS. It was found that due increasing competition in the pricing of products, remanufacturers focus on EOS in the reverse supply chain.

Diaz and Marsillac (2017) built a Monte Carlo simulation to create a strategic decision support model for remanufacturing and considered EOS for the number of items remanufactured. The model is based on the news vendor problem and includes stochastic demand and supply. Provisions for modeling EOS from a learning curve, probabilistic collection effort, product obsolescence, revenue and salvage value was made. The model has the likelihood of increasing revenue streams
Table 3.1 summarizes the key characteristics of the papers discussed above.

3.2.2 Reliability and quality issues

One of the major hurdles faced by remanufacturers is assessing the quality and reliability of returned products. Some products may be returned in relatively good condition while others may be damaged beyond repair. If the remanufacturer is prepared for returns of varying quality, then it has a greater ability to generate profit from the returns collected. To assist remanufacturers and improve the CLSC, several authors have focused on designing CLSC networks when facing:

- Return quality uncertainty (Jeihoonian, Zanjani, and Gendreau, 2017; Pedram, Yusoff, Udoncy, Mahat, Pedram, and Babalola, 2017),
- Return rates dependent on price and quality levels (Genc and De Giovanni, 2017), and
- price & Quality dependent demand (Maiti and Giri, 2017).

Table 3.1: Summary table for EOS papers

Citation	**Method**	**Location of EOS**	**Settings**				**Problem solved**	**Industry**
			Multi-Period	**Single product**	**Multi-product**	**Capacitated**		
Vieira et al. (2015)	SCAnt-NLDesign, MILP	Considered in transportation distance, transported quantities, and warehouse and disassembly centre capacity			*	*	Using Ant colony optimization in the design of CLSC while considering nonlinear dimensioning factors.	
Diaz and Marsillac (2017)	Monte Carlo method	Characterization of EOS from a learning curve	*		*	*	Strategic decision support model for remanufacturing	electronics
Georgiadis and Athanasiou (2013)	Simulation-based Systems dynamics optimization	EOS at the collection and remanufacturing facility			*	*	long term capacity planning	electronics and automotive products
Bucci et al. (2014)	Heuristics, MINLP	EOS at the recycling plant		*		*	Facility location in reverse logistics	Carpet
Wu (2015)	Hotelling model	Remanufacturer chooses to pursue EOS in the sales market or recycling market	*	*		*	Price competition between OEMs and remanufacturer	

Other studies also focused on measuring the perceived quality of remanufactured products (Hazen, Boone, Wang, and Khor, 2017). Most studies incorporate quality grading but very few studies other than Hazen et al. (2017) have considered reliability issues.

Jeihoonian et al. (2017) built a two-stage stochastic mixed-integer programming model to design a CLSC for modular products. The model accounts for uncertainty on return quality using discrete scenarios. To work with the large number of scenarios in the model, a scenario reduction scheme focussing on important scenarios using modified Euclidean distance. Surrogate constraints along with Pareto optimal cuts were used to improve the L-shaped technique used to solve the stochastic program.

Genc and De Giovanni (2017) study price and technology based demand and returns in a CLSC model. They developed a two-period Stackelberg game to model the CLSC network where the manufacturer is the supply chain leader and return rates are dependent on price and quality levels. Differences between the collection of EOL products by the manufacturer and the retailer are discussed and suggestions are made to convert from passive to active returns collection. To make the model more realistic, the authors also considered the effects of retail competition on an organization's strategy and profit.

Maiti and Giri (2017) consider a two stage CLSC with one manufacturer, one retailer and a single product. The retailer sets the selling price with a variable markup on the wholesale price set by the manufacturer, whereas the manufacturer has a fixed mark-up on the production costs. Two-way product recovery is considered as the retailer collects returned products from customers and employs exchange offers to gather more used goods. The model is analyzed using manufacturer led and retailer led Stackelberg games, decentralized - Nash game and centralized - cooperative games. By comparing the different structures, the best outcome is found. It was found that the whole system gains in the cooperation case; manufacture-led channels are beneficial primary to manufacturers while retailer led channels are best in decentralized scenarios.

Pedram et al. (2017) developed a CLSC model for profit maximization and waste minimization. An example from the tire industry was used to show the applicability of the model. With tire retreading, the energy and raw materials used in the manufacturing of a new tire can be conserved. The proposed model identifies the location, number and capacity of collection, distribution, retreading and recycling facilities.

Hazen et al. (2017) developed a multidimensional technique to measure the quality of a remanufactured product as perceived by consumers. The quality measure is based on product features, performance, serviceability and lifespan. Factors to measure reliability and durability have also been included. Products such as cell phones (personal electronics), copy machines (business electronics), lathes (industrial items), engine (automotive parts) and other items were included in this study.
Venkatadri et al. (2017) studied the impact of design for disassembly, BOM for product decomposition into parts considering a secondary market for refurbished goods and product/part reliability and greenness in their reverse logistics network design.
Table 3.2 below summarizes the papers that dealt with reliability and/or quality issues.

3.2.3 Transshipment issues

According to Hillier and Lieberman (2015), the transshipment problem is a variation of the minimum cost flow problem wherein products pass through intermediate transfer points between a product source and its destination. Benefits of transshipment include reduction in the total network costs (Tracht, Mederer, and Schneider, 2011; Jabbarzadeh et al., 2018), increased service levels (Tracht et al., 2011) and reduction in disruption risk (Jabbarzadeh et al., 2018). Although transshipment provides the above benefits and streamlines CLSC design, only a few researchers have incorporated this strategy in their models. Lateral transshipment was studied by Tracht et al. (2011) and Jabbarzadeh et al. (2018).

Table 3.2: Summary of papers dealing with quality and reliability issues

Citation	**Method**	**Reliability**	**Quality**		**Settings**					**Problem solved**	**Industry examples**
			Grading	**Pricing**	**Single Period**	**Multi Period**	**Multi component**	**Single product**	**Multi product**		
Jeihoonian et al. (2017)	Two-stage stochastic mixed-integer programming model		*		*		*		*	CLSC network design for modular structured products	Washing Machine
Hazen et al. (2017)	Factor analysis	Factor for reliability and durability is included	*				*		*	Measuring perceived quality of remanufactured products	Automotive, electronics, power tools
Genc and De Giovanni (2017)	Two period stackelberg game		*	*	*			*		CLSC design with return rate dependent on price and quality	
Maiti and Giri (2017)	CLSC model is analyzed using decentralized (Nash Game), centralized (Co-operative game) , manufacturer and retailer led stackelberg games		*	*		*		*		Two stage CLSC with two way product recovery	Engine remanufacturing
Pedram et al. (2017)	MILP		*		*				*	CLSC network design with waste minimization and profit maximization	Tire

Tracht et al. (2011) developed a simulation model to find the total costs and service levels in a CLSC network. The authors then studied the effects of lateral transshipment on a repairable item. The proposed model had distribution warehouses and a central warehouse. When the distribution warehouse is out of stock for a spare part, it is sent from the central warehouse. If the spare part is not present in either warehouse, then it is loaned from a competitor. The work considered reactive transshipment and accounted for stock-out costs linked to loan duration. Transshipment was found to reduce the total cost of the model. It was also found that higher loan costs resulted in longer stock outs.

Jabbarzadeh et al. (2018) consider a CLSC subject to random disruptions and proposed a stochastic robust optimization model to minimize costs in the network due to these disruptions. Lateral transshipment was found to be useful to overcome disruption risks. A Lagrangian relaxation algorithm was used to solve the robust model and using data from a glass manufacturing facility, the authors showed the effectiveness of their methodology. They suggest that with some planning for future disruptions, organizations can save substantial money.

Other studies incorporating transshipment in their work include Jayaraman, Guide Jr, and Srivastava (1999), who considered facility location, transshipment and optimal stocking of remanufacturable products in the design of a CLSC. Data from a small electronics product remanufacturer in North America was used to test the model. The model consists of demand-driven flows of remanufactured products to consumers and supply-driven flows of core/used products from consumers to remanufacturers. The authors identified variables such as demand for remanufactured product and quantity of returns collected as being critical to the CLSC design. The importance of having sufficient quantities of cores on streamlining CLSC operations was emphasized.

Zaarour, Melachrinoudis, Solomon, and Min (2013) found the optimal collection periods at Initial Collection Points (ICP) before returned products are transhipped to a Centralized Return Center (CRC). A balance is to be maintained between the inventory holding costs at the ICP and the transportation quantity discounts offered on the product shipped to a CRC. Using a discrete collection period model, the authors simulated a reverse network for collection of returned items with transshipment and consolidation over multiple planning horizons and multiple freight discount points. The proposed model identified the link between product return rate and the ideal collection period.

Cardoso, Barbosa-Póvoa, and Relvas (2016) incorporated transshipment between warehouses in CLSC design while considering financial risk and overcoming demand uncertainty. The model simultaneously maximizes the expected net present value (ENPV) of the network while minimizing financial risk. Four risk measures were used in this study: conditional value-at-risk, variance, variability and downside risk. To show the trade-off between both objectives, an approximation of the Pareto optimal curve is developed using the augmented epsilon-constrained method. A real-life supply chain in Europe was studied and suggestions to increase facility capacity (indirectly reducing the ENPV) to reduce risk were put forth.

Even though the transshipment strategy is widely used in the forward logistics literature and can be enormously beneficial to the CLSC, we find that this concept has not been used much in reverse logistics literature. To gain the benefits of transshipment, we incorporate this strategy into a CLSC network with IRDCs facilities of different capacities, as described in the next section.

3.3 Framework of the CSLC network with economies of scale, reliability and transshipment considerations

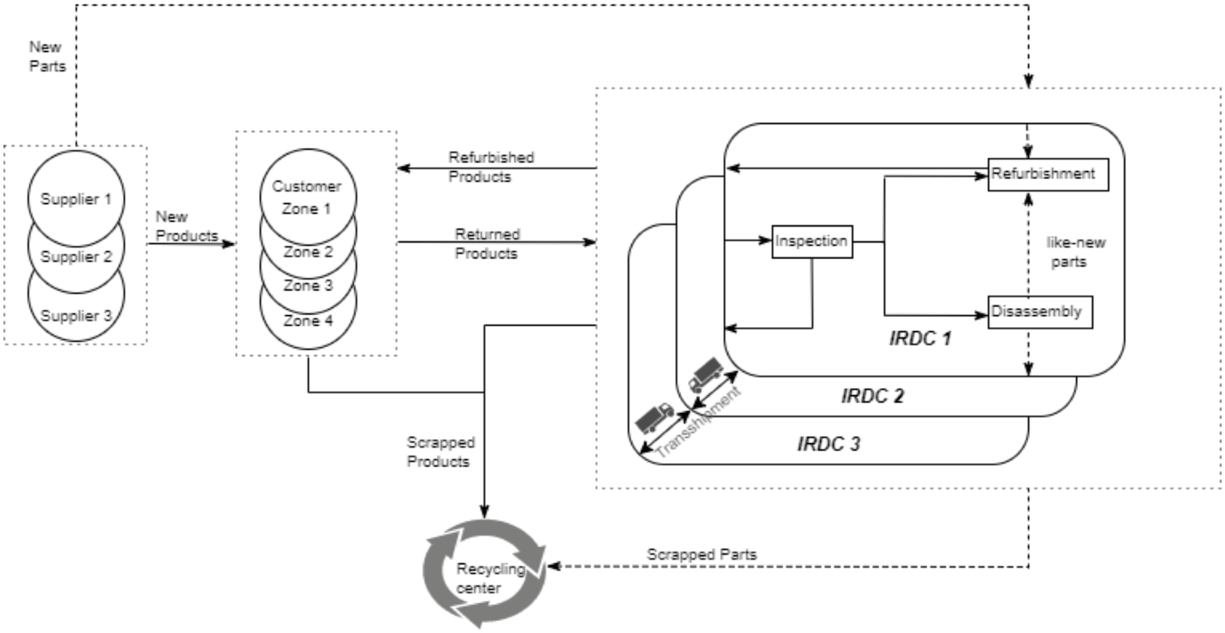
We now look at a CLSC network with economies of scale, reliability and transshipment considerations that extends the model in Venkatadri et al. (2017). The network comprises suppliers, CZs, IRDCs and a recycling centre as illustrated in Figure 3.1.

Customers return a proportion of used products to collection depots situated at the CZs. The return rate for different products may vary in different CZs. Products are sent from the CZs to either the recycling centre or an IRDC for inspection. After inspection, these products are refurbished, disassembled, or recycled.

Table 3.3: Summary table for transshipment papers

Citation	Method	Transshipment	Settings								Problem solved	Industry examples
			Single Period	Multi Period	Single component	Multi component	Single product	Multi product	Capacitated	Uncapacitated		
Jayaraman et al. (1999)	MILP	*	*					*	*		CLSC design with transshipment, production, facility location and stocking of optimal quantity of products	Electronics
Tracht et al. (2011)	Simulation model	Transshipment is reactive and occurs when there is a stock out at a distribution warehouse			*		Model based on spare parts		*		Finding total costs and service levels in CLSC for repairable items	Electronic aircraft device
Zaarour et al. (2013)	Discrete Collection Period Model (Numerical analysis)	Transshipment from an initial collection centre to a centralized facility		*				*		*	Determine optimal collection period before product is transshipped to a centralized facility	
Cardoso et al. (2016)	MILP	Transshipment between warehouses		*		*		*	*		Design a CLSC with financial risk measures	Real case study based in Europe
Jabbarzadeh et al. (2018)	Stochastic robust optimization model	Lateral transshipment between production centres		*				*	*		Design a CLSC to overcome disruption risks	Glass

Figure 3.1: Representation of the Closed-loop supply chain network



Due to economies of scale, several IRDC sizes may be considered. Different size IRDCs correspond to different inspection and disassembly capacities, with the general assumption that there are EOS in increasing the size of the IRDC . It is assumed that the disassembly capacity of the IRDCs is less than their inspection capacities. Therefore, inspected products may be transshipped to another open IRDC.

The disassembly process provides like-new parts for refurbishing or parts to be recycled. If the number of like-new parts from the disassembly process is insufficient then new parts are purchased from suppliers, implying flows from the suppliers to the IRDCs. Finally, refurbished goods are sent from the refurbishing stage of the IRDCs to the CZs. Therefore, demand at the CZs is satisfied either from new products purchased from suppliers or from refurbished products.

The assumptions used in the creation of the CLSC model are:

- Demand satisfaction of new products is mandatory.
- Demand for refurbished goods may or may not be satisfied.
- Location of suppliers, CZs, and the recycling centre (RC) are predefined.

- Recycling costs are included in the shipping cost to a recycling centre.
- The failure rate of a part/product affects its reliability and hence a higher failure rate results in lower reliability. Part reliability is computed from the proportion of parts which need to be replaced at the refurbishment stage of an IRDC (Venkatadri et al., 2017).

3.4 Model formulation

The following notation is used in the formulation of the closed-loop supply chain network model.

Indices

l, i	Potential IRDC locations
k	CZs
m	Products
p	Parts
s	Size of an IRDC

Parameters

a_{pl}	Freight on board destination cost of part p delivered to IRDC l
c_{mk}	Unit shipping cost of new product m delivered to CZ k
c_{mlk}	Unit shipping cost of refurbished product m delivered from IRDC l to CZ k
c_{mkl}	Unit shipping cost of product m from CZ k to IRDC l
c_{ml}	Unit shipping cost of scrapped product m from IRDC l to Recycling centre (RC)
c^{e}_{mk}	Unit shipping cost of returned product m from CZ k to RC
c_{pl}	Unit shipping cost of scrapped part p from IRDC l to RC
C_m	Supply capacity for new product m
C_p	Supply capacity for new part p
C_{ls}	Inspection capacity of IRDC l of size s
C^{D}_{ls}	Disassembly capacity of IRDC l of size s

d_{mk}	Demand for new product m in CZ k
d^R_{mk}	Demand for refurbished product m in CZ k
D_{ml}	Unit disassembly cost of product m at IRDC l
η_{mk}	Unit lost sale cost for refurbished product m in CZ k
F_{ls}	Fixed cost of opening IRDC l of size s
F^D_{ls}	Fixed cost of installing disassembly line at IRDC l of size s
γ_p	Fraction of part p requiring replacement at the refurbishment stage
I_{ml}	Unit inspection cost of product m at IRDC l
π_m	Unit purchasing price of product m
r_{mk}	Return rate of product m from CZ k
R_{ml}	Unit refurbishing cost of product m at IRDC l
ρ_{mk}	Unit sale price of new product m in CZ k
ρ^R_{mk}	Unit sale price of refurbished product m in CZ k
σ_{pm}	Binary parameter indicating whether part p is in product m
θ_p	Fraction of good parts of type p recovered from disassembly
T_{mli}	Unit transshipment cost of product m from IRDC l to IRDC i

Decision variables

δ^-_{mk}	Shortfall of refurbished products m in CZ k
f_{ml}	Quantity of products m inspected at IRDC l
f_{mkl}	Quantity of products m returned from CZ k to IRDC l
f^R_{mlk}	Quantity of refurbished products m sent from IRDC l to CZ k
f^R_{ml}	Quantity of product m refurbished at IRDC l
f^D_{ml}	Quantity of product m disassembled at IRDC l
f_{pl}	Quantity of new part p shipped from suppliers to IRDC l
g_{ml}	Quantity of scrapped product m shipped from IRDC l to RC
g_{pl}	Quantity of scrapped part p shipped from IRDC l to RC
o^e_{mk}	Quantity of returned products m shipped from CZ k to RC
X_{mli}	Quantity of product m transshipped from IRDC l to IRDC i

$$Y_{ls} = \begin{cases} 1 & \text{if IRDC of size } s \text{ is opened at location } l \\ 0 & \text{otherwise} \end{cases}$$

$$Z_{ls} = \begin{cases} 1 & \text{if disassembly line is installed at IRDC } l \text{ of size } s \\ 0 & \text{otherwise} \end{cases}$$

The mathematical formulation for the maximization of total profit in the network is as follows:
Maximize Profit:

$$\begin{aligned} Z = & \sum_{m\in M}\sum_{k\in K}\rho_{mk}d_{mk} + \sum_{m\in M}\sum_{k\in K}\sum_{l\in L}\rho^{R}_{mk}f^{R}_{mlk} - \sum_{l\in L}\sum_{s\in S}F_{ls}Y_{ls} \\ & - \sum_{l\in L}\sum_{s\in S}F^{D}_{ls}Z_{ls} - \sum_{m\in M}\pi_m\sum_{k\in K}d_{mk} - \sum_{m\in M}\sum_{k\in K}c_{m,k}d_{mk} - \sum_{m\in M}\sum_{k\in K}\sum_{l\in L}c_{mkl}f_{mkl} \\ & - \sum_{m\in M}\sum_{k\in K}c^{e}_{mk}o^{e}_{mk} - \sum_{m\in M}\sum_{k\in K}\sum_{l\in L}I_{ml}f_{mkl} - \sum_{m\in M}\sum_{l\in L}R_{ml}f^{R}_{ml} \\ & - \sum_{m\in M}\sum_{l\in L}D_{ml}f^{D}_{ml} - \sum_{m\in M}\sum_{l\in L}\sum_{k\in K}c_{mlk}f^{R}_{mlk} - \sum_{p\in P}\sum_{l\in L}a_{pl}f_{pl} \\ & - \sum_{m\in M}\sum_{l\in L}c_{ml}g_{ml} - \sum_{p\in P}\sum_{l\in L}c_{pl}g_{pl} - \sum_{m\in M}\sum_{k\in K}\eta_{mk}\delta^{-}_{mk} \\ & - \sum_{m\in M}\sum_{l\in L}\sum_{i\in L, i\neq l}X_{mli}T_{mli} \end{aligned} \tag{3.1}$$

Subject to:

$$\sum_{k\in K} f_{mkl} = f_{ml} \qquad \forall m,l \tag{3.2}$$

$$Z_{ls} \leq Y_{ls} \qquad \forall l,s \tag{3.3}$$

$$f_{ml} + \sum_{i\in L, i\neq l} X_{mil} = f_{ml}^{R} + f_{ml}^{D} + g_{ml} + \sum_{i\in L, i\neq l} X_{mli} \qquad \forall m,l \tag{3.4}$$

$$X_{mli} \leq f_{ml} \qquad \forall m,l,i,i\neq l \tag{3.5}$$

$$f_{ml}^{R} = \sum_{k\in K} f_{mlk}^{R} \qquad \forall m,l \tag{3.6}$$

$$\gamma_p \sum_{m\in M} \sigma_{pm} f_{ml}^{R} = f_{pl} + \theta_p \sum_{m\in M} \sigma_{pm} f_{ml}^{D} \qquad \forall p,l \tag{3.7}$$

$$g_{pl} = (1-\theta_p) \sum_{m\in M} \sigma_{pm} f_{ml}^{D} \qquad \forall p,l \tag{3.8}$$

$$\sum_{l\in L} f_{mlk}^{R} = d_{mk}^{R} - \delta_{mk}^{-} \qquad \forall m,k \tag{3.9}$$

$$o_{mk}^{e} + \sum_{l\in L} f_{mkl} = r_{mk} d_{mk} \qquad \forall m,k \tag{3.10}$$

$$\sum_{s\in S} Y_{ls} \leq 1 \qquad \forall l \tag{3.11}$$

$$\sum_{k\in K} d_{mk} \leq C_m \qquad \forall m \tag{3.12}$$

$$\sum_{l\in L} f_{pl} \leq C_p \qquad \forall p \tag{3.13}$$

$$\sum_{m\in M} f_{ml} \leq \sum_{s\in S} C_{ls} Y_{ls} \qquad \forall l \tag{3.14}$$

$$\sum_{m\in M} f_{ml}^{D} \leq \sum_{s\in S} C_{ls}^{D} Z_{ls} \qquad \forall l \tag{3.15}$$

$$f_{ml}, f_{ml}^{R}, f_{ml}^{D}, g_{ml}, f_{mlk}^{R}, \delta_{mk}^{-} \geq 0 \qquad \forall m,k,l,p \tag{3.16}$$

$$f_{pl}, g_{pl}, f_{mkl}, o_{mk}^{e}, X_{mli} \geq 0 \qquad \forall m,k,l,i,p \tag{3.17}$$

$$Y_{ls}, Z_{ls} \in \{0,1\} \qquad \forall l,s \tag{3.18}$$

The model maximizes the total profit for the network given in equation (3.1). The total profit is the total revenue obtained by selling new and refurbished products minus total costs. The total cost includes costs related to establishing facilities, purchasing of new products and parts from suppliers, transportation, transshipment,

costs for processing products during inspection, refurbishment and disassembly stages, and lost sales cost for not satisfying demand of refurbished products.
Constraint (3.2) ensures that all products at IRDC are inspected. Constraint (3.3) ensures that a disassembly line is opened only when an IRDC is established. Constraint (3.4) ensures flow balance at the IRDCs, with transshipment. The LHS of the constraint counts the number of products inspected or transshipped from another location. The RHS of the constraint sums up the number of products refurbished, disassembled, scrapped and transshipped to another location. Constraint (3.5) ensures that the number of products transshipped is less than the number of products inspected at the IRDC. Constraint (3.6) ensures that all refurbished products from the IRDCs are sent to CZs. Constraint (3.7) ensures that the total quantity of parts used in refurbishing activities is equal to the quantity of new parts purchased from suppliers and like-new parts obtained from disassembly. Constraint (3.8) ensures that scrapped parts from the disassembly process is sent to the recycling centre. Constraint (3.9) shows that lost sales are acceptable in case of refurbished products. Constraint (3.10) ensures that all products returned from the CZs are either sent to the recycling centre or IRDCs. Constraint (3.11) ensures that only one IRDC of a specific size can be opened at a location. Constraints (3.12)-(3.15) are capacity constraints on the supplier capacity for new products and new parts, IRDC capacity for inspection and IRDC capacity for disassembly. Constraints (3.16) and (3.17) enforce non-negativity and (3.18) enforces binary restrictions on corresponding decision variables.

Flow variables such as f_{mkl}, f^R_{ml} are modeled as continuous instead of integer. As the decision maker is unable to ensure that flow variables are precisely implemented over a multi-horizon design interval, continuous variables are preferred. Also, the network structure makes linear programming (LP) relaxations very tight and thus there are negligible difference between objective function values (Venkatadri et al., 2017)

3.5 Numerical examples

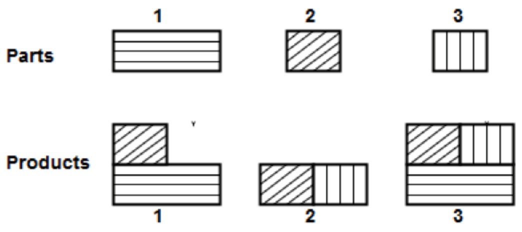
3.5.1 Verification phase

A number of experiments are carried out on the CLSC network model with EOS to provide insights into the behaviour of the model for an example case with 3 CZs, 3 IRDCs, and 3 products. From a set of 3 parts, different multi-component products are formed as seen in Figure 3.2 and Table 3.4.

The network model considers EOS in locating IRDCs. For the following experiments, one IRDC size (from small, medium and large) can be chosen at a location. In the EOS case, when the inspection capacity of an IRDC (C_{ls}) increases by two, the fixed cost of opening an IRDC (F_{ls}) increases by a factor of less than two. The parameter values for the network with and without EOS are shown in Table 3.5, Table 3.6, and Figure 3.3 for the same inspection and disassembly capacities of IRDCs.

We assume that disassembly lines are installed only in medium and large size IRDCs. To enforce no disassembly at the small IRDCs, the fixed cost F^D_{ls} is kept very high for this case. Other important parameters are shown in Tables 3.7 and 3.8. All models were implemented in GUSEK© (GLPK© Under Scite Extended Kit) 0.2 and saved as .mps files which were then run on Gurobi© 7.0.2 on an Intel(R)© Core i5-5250U CPU running at 1.6 GHz with 8.00 GB RAM.

Figure 3.2: Multi component products: assembled from multiple parts



The verification experiment shows the opening of different sizes of IRDCs with the increase in demand for new products (d_{mk}) while the demand for refurbished

Table 3.4: σ_{pm}

	Parts		
Product	1	2	3
1	*	*	
2		*	*
3	*	*	*

Table 3.5: Fixed costs and capacities for an IRDC - without EOS

IRDC size	C_{ls}	C_{ls}^D	F_{ls}	F_{ls}^D
Small	50,000	0	500,000	1,000,000
Medium	100,000	50,000	1,000,000	300,000
Large	200,000	100,000	2,000,000	600,000

Table 3.6: Fixed costs and capacities for an IRDC - with EOS

IRDC size	C_{ls}	C_{ls}^D	F_{ls}	F_{ls}^D
Small	50,000	0	500,000	1,000,000
Medium	100,000	50,000	800,000	300,000
Large	200,000	100,000	900,000	400,000

Figure 3.3: Relationship between inspection capacity of an IRDC and its fixed cost of opening

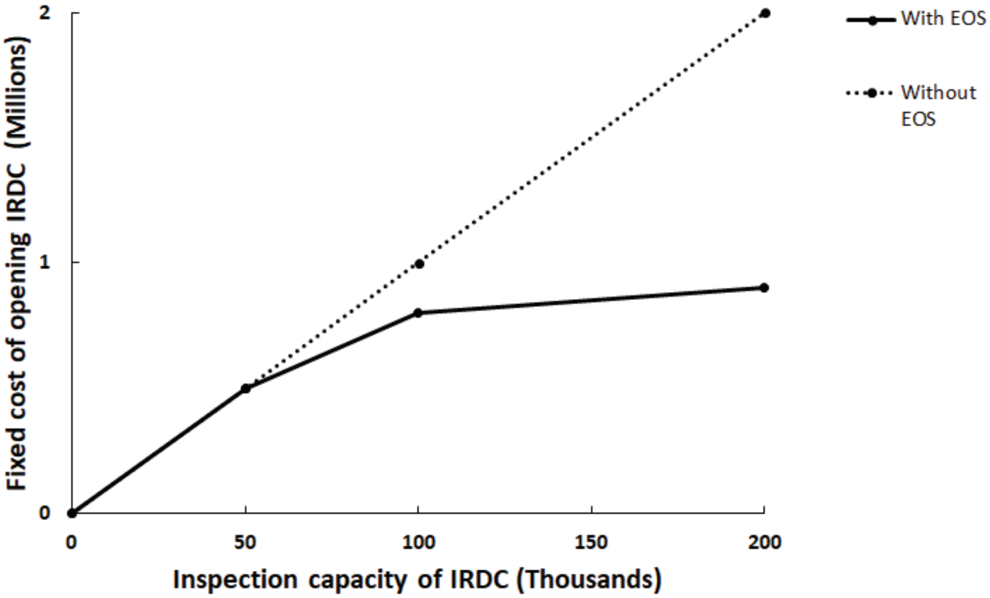


Table 3.7: Parameters table

Parameter	Value
π_m	100
c_{mk}	2 to 5
c_{mlk}	2 to 4
a_{pl}	100 for part 1/3 and 250 for part 2
c_{mkl}	2 to 4 for IRDC 1 and 3 , but 20 to 40 for 2nd IRDC
c_{ml}	195
c^{e}_{mk}	100
c_{pl}	5
C_m	1,000,000
C_p	100,000
r_{mk}	0.2 to 0.7
γ_p	o.5
θ_p	0.4 to 0.6
ρ_{mk}	300
ρ^{R}_{mk}	250
η_{mk}	100
T_{mli}	10

Table 3.8: Refurbishment, inspection and disassembly costs across all IRDC locations and sizes

Products	R_{ml}	I_{ml}	D_{ml}
1	30	30	20
2	25	25	17
3	20	30	15

Table 3.9: Legend for IRDC size

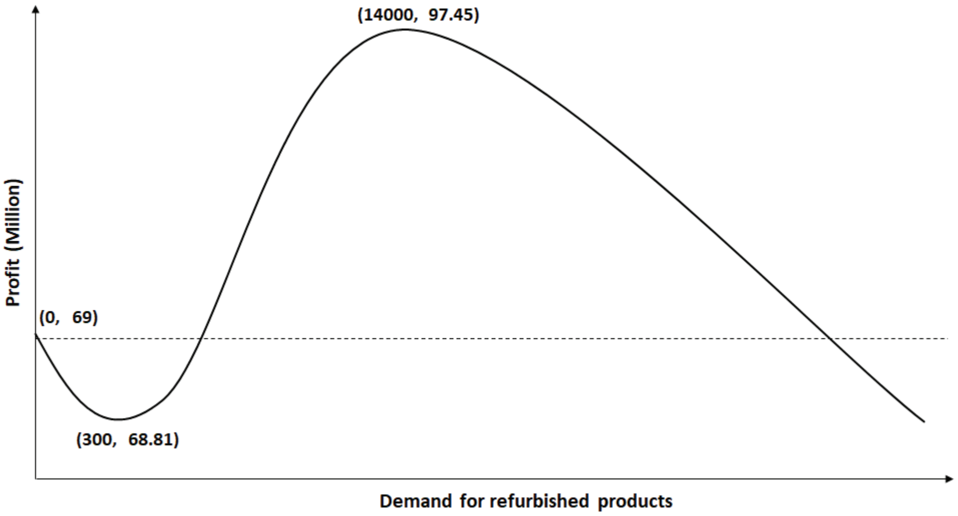
S	Small IRDC
M	Medium IRDC
L	Large IRDC
D	Disassembly Line

Table 3.10: Variation in the type of IRDC opened

IRDC location	Demand for new products d_{mk}							
	3,000	10,000	30,000	60,000	70,000	90,000	125,000	1,50,000
1	S	M+D		S	L+D	L+D	L+D	L+D
2							M+D	L+D
3			L+D	L+D	M	L+D	L+D	L+D

products (d^R_{mk}) is kept constant at 100,000 units. As seen in the Table 3.10, when the demand for new products $d_{mk} = 3{,}000$ units, a small IRDC is opened at location 1. As d_{mk} is increased to 10,000 units, a medium IRDC is opened with a disassembly line at location 1. With a further increase in d_{mk} to 30,000 units, a large IRDC is opened with a disassembly line at location 3. At higher values of d_{mk} such as 60,000 units, IRDCs are opened at multiple locations: a small IRDC at location 1 and a large IRDC along with a disassembly line at location 3. For excessively large values of d_{mk} reaching 150,000 units, large IRDCs along with disassembly lines are opened at all three locations. As the d_{mk} increases, the size and number of IRDCs opened also increase.

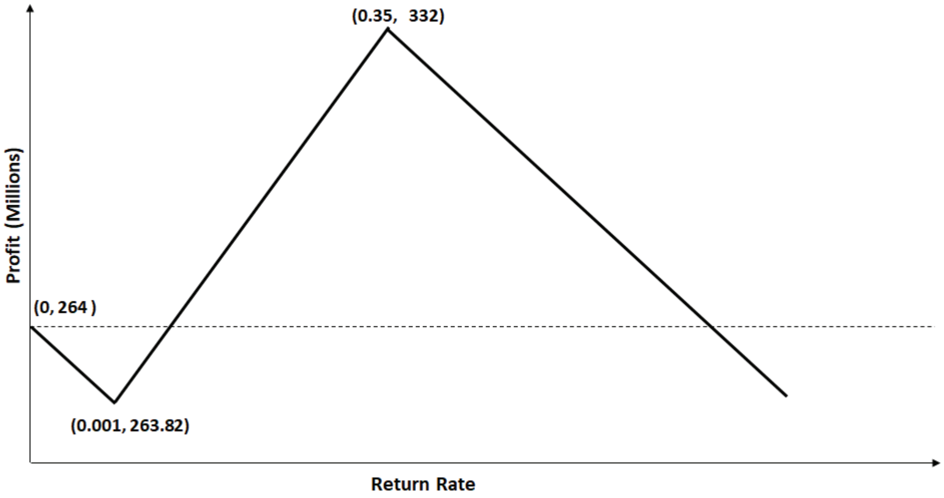
Figure 3.4: Economical operating range for reverse flow with EOS



Based on Venkatadri et al. (2017), an experiment is conducted to find the economical operating range for reverse flow with EOS. The demand for new products d_{mk} is 50,000 units in this experiment. Trends similar to the original experiment were obtained as depicted in Figure 3.4. When d^R_{mk} is 0, the profit obtained is \$69,000,000. The profit decreases as d^R_{mk} is increased upto 300 units due to lost sales. At this point an IRDC is opened and demand for refurbished products is satisfied. The profit then increases till d^R_{mk} is 14,000 units. After this point as d^R_{mk} increases , there is a decrease in profit as the capacity of the IRDC is reached and there is increasing lost sales.

Another verification experiment is run to investigate the effects of varying return rate(r_{mk}) on the profit function. The results are illustrated in Figure 3.5. Here d_{mk} is 200,000 units and d^R_{mk} is 100,000. As the return rate increases the profit decrease to the its least value at $r_{mk} = 0.001$. At this point there are enough returns and an IRDC is opened. With the ability to satisfy the demand for refurbished products the profit increases with an increase in return rate upto $r_{mk} = 0.35$. Beyond this point the profit function decreases as excessive returns have to be discarded at a cost.

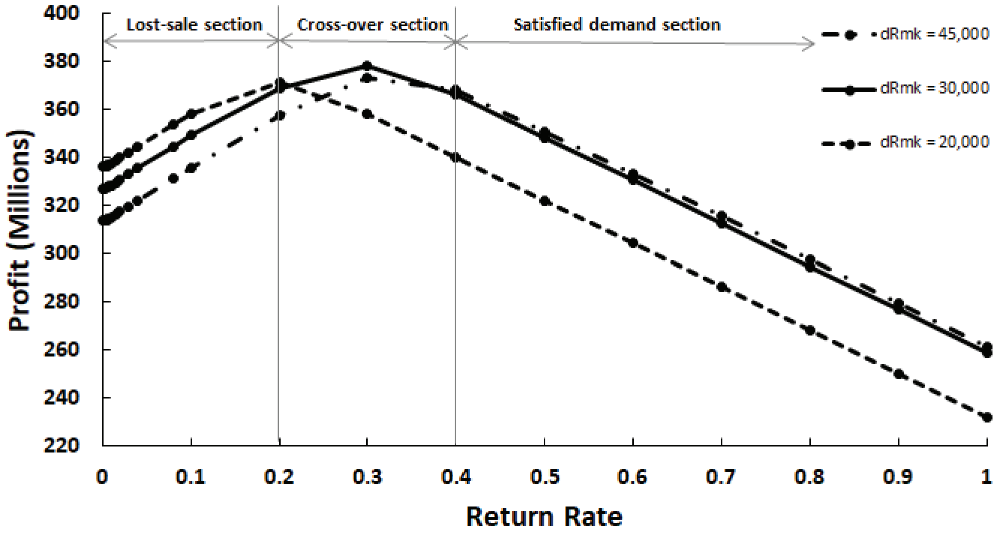
Figure 3.5: Profit as a function of return rate



The profit function is observed while changing the return rate for three different values of d^R_{mk}. From Figure 3.6, it can be seen that there are three different regions namely lost-sales, a cross-over region and a satisfied demand region.

From the above experiments it can be concluded that the current model produces results which are similar to the results obtained by Venkatadri et al. (2017). We now look into the effects of EOS and possibility of transshipment between IRDCs.

Figure 3.6: Profit as a function of return rate for diverse d^R_{mk}



3.5.2 Experiment 1 - Investigating the impact of EOS

In this experiment, the effect of economies of scale on locating IRDCs is studied. The model has the ability to choose one IRDC at a location from three given sizes (small, medium and large). The profit in the presence and absence of economies of scale is calculated while changing the demand for refurbished products (d^R_{mk}). Due to increasing d^R_{mk}, the profit for the network increases. But there is a difference in profit between the cases with EOS and the one without EOS. The variation in the IRDCs opened and the difference in profit for conditions with and without EOS is summarized in Table 3.11.

Figure 3.7 shows the difference in profit from both scenarios versus the demand for refurbished products. The difference in profit is 0 when d^R_{mk} is below 200 units. At d^R_{mk} = 300 units, the difference in profit increases to \$39,450. Between d^R_{mk} = 400 units to d^R_{mk} = 5,000 units, the difference in profit is constant at \$200,000. Between d^R_{mk} = 7,000 units to d^R_{mk} = 11,000 units, the difference in profit is constant at \$1,300,000. Between d^R_{mk} = 12,000 units to d^R_{mk} = 18,000 units, the difference in profit is constant at \$1,500,000. With further increase in d^R_{mk}, the difference in profit increases steadily to reach a value of \$2,600,000.

EOS is beneficial when d^R_{mk} increases beyond 200 units. With EOS, larger and fewer IRDCs are opened as compared to the case without economies of scale.

Figure 3.7: Effects of economies of scale on the difference in profit

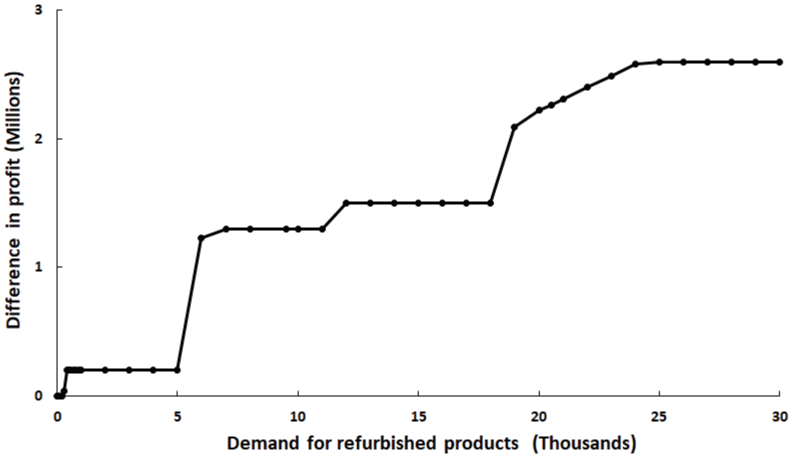


Table 3.11: IRDC opened with and without Economies of Scale (EOS)

d^R_{mk}	IRDC opened with EOS	IRDC opened Without EOS	Difference in Profit
200	none	none	-
300	M+D	S	39,450
400	M+D	M+D	200,000
5,000	M+D	M+D	200,000
6,000	L+D	S, M+D	1,226,000
7,000	L+D	2M+D	1,300,000
11,000	L+D	2 M+D	1,300,000
19,000	2 L+D	S, M+D, L+D	2,094,000
23,000	2 L+D	S, M+D, L+D	2,490,000
25,000	2 L+D	2 L+D	2,600,000

3.5.3 Experiment 2 - Impact of transshipment

Transshipment between IRDCs results in monetary benefits to the CLSC network. In this model, inspected products are transshipped from one IRDC to another as the disassembly capacity of an IRDC is saturated. Transshipment is affected by the transshipment cost between IRDCs (T_{mli}) and the disassembly capacity of IRDCs (C^D_{ls}) .

In the first part of the experiment, the mathematical model is run with transshipment and subsequently without transshipment as the transshipment cost is varied to \$1 , \$10 and \$15. The demand for new products (d_{mk}) is 300,000 units. The profit in all iterations is noted while varying d^R_{mk}. The profit achieved with and without transshipment are subtracted from each other, and the difference in profit is plotted versus d^R_{mk}. Consider the case with transshipment cost of \$10. (The behaviour of curves with transshipment cost of \$1 and \$15 is similar to the curve with transshipment cost of \$10). From Figure 3.8, we notice that when d^R_{mk} = 11,950 there is sufficient quantity of products for transshipment to occur. As the value of d^R_{mk} increases, the quantity transshipped products increases and the difference in profit increases and reaches a maximum value of \$800,000. Between d^R_{mk} = 19,000 to 27,000 the difference in profit is constant at \$800,000. After d^R_{mk} = 27,000, the quantity transshipped decreases and difference in profit decreases too and reaches a minimum value of \$80,000. Between d^R_{mk} = 40,000 to 50,000, the difference in profit is constant at \$80,000. With further increase in d^R_{mk} transshipped quantities increases and difference in profit rises to a maximum of \$400,000. But the rise is less as compared to the previous case due to saturation of inspection and disassembly capacities. Thus, the rise and fall of the difference in profit is governed by the quantities transshipped between IRDCs. Due to economies of scale, the model chooses between building smaller facilities and no transshipment and larger facilities with transshipment. It is observed that with lower transshipment costs, higher difference in profits are achieved and the transshipment begins earlier (as seen in the smaller graph in 3.8). Higher transshipment costs result in lesser difference in profit values and transshipment begins later. Very high transshipment costs preclude the possibility of transshipment in the network.

Since the disassembly capacity of IRDCs (C^D_{ls}) affects transshipment, we run the model with d_{mk} = 3,00,000 units and transshipment cost is \$10 under different C^D_{ls} scenarios as seen in Table 3.12.

Figure 3.8: Effects of varying transshipment cost on the difference in profit

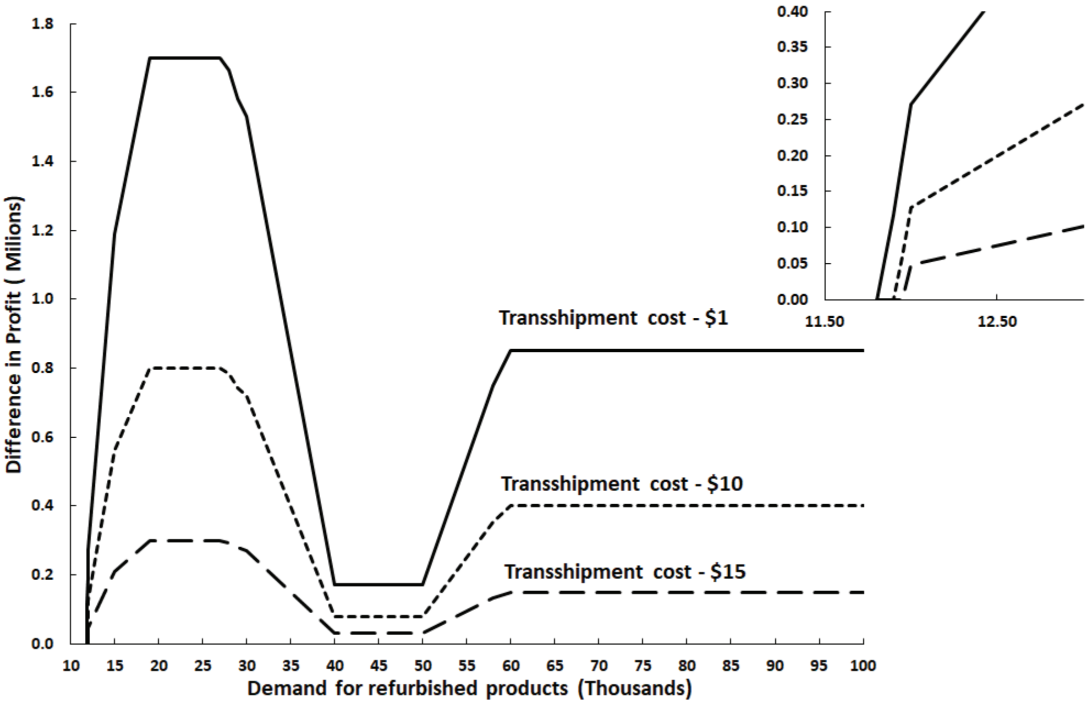
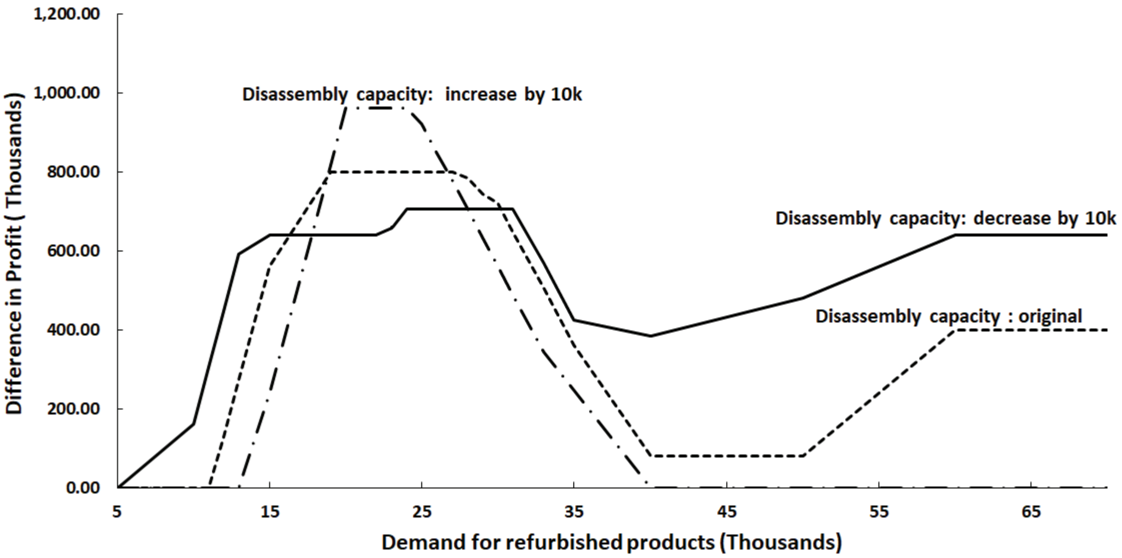


Table 3.12: C_{ls}^D for different scenarios

IRDC	Scenario 1	Scenario 2	Scenario 3
Small	–	–	–
Medium	15,000	25,000	35,000
Large	40,000	50,000	60,000

In each scenario the profit with and without transshipment is computed while varying the demand for refurbished products(d_{mk}^R). The difference in profit is plotted versus d_{mk}^R for different C_{ls}^D scenarios as seen in Figure 3.9. The rise and fall of the graphs can be attributed to the increase and the decrease in the quantity of products transshipped respectively. Lower disassembly capacities force the model to begin transshipment earlier as compared to the model having a larger disassembly capacity. But higher difference in profits are achieved in models with large disassembly capacities.

Figure 3.9: Effects of varying disassembly capacity of IRDC on the difference in profit



3.5.4 Experiment 3 - Investigating impact of part reliability

The effects of varying γ_p on profit is studied in this experiment. γ_p represents the fraction of parts p requiring replacement at the refurbishment stage of an IRDC and is, therefore, a measure of part unreliably. Increase in γ_p results in an increase in part unreliability. The experiment is performed with d_{mk} = 50,000 units and $r_{mk} =$ 0.7. Different scenarios are simulated by changing the value of d^R_{mk}. Different values of d^R_{mk} show the relationship between profit and γ_p.

1. For d^R_{mk} = 100, the profit remains constant and changes in γ_p have no effect. The demand for refurbished products is so low that no IRDC exists. Thus, changes in γ_p have no effect on the total profit.

2. For d^R_{mk} = 5,000, the profit first starts decreasing with an increase in γ_p and the small open IRDC gets saturated. At γ_p = 0.03, a medium size IRDC is opened. This larger IRDC helps to achieve an increase in profit as there is no purchase of new parts from external suppliers and parts obtained from disassembly are sufficient to produce refurbished products. Between γ_p = 0.5 to 0.6 there is a transition from a medium to a large IRDC and hence there is a small slowdown in the rate of increase of the profit due to higher fixed costs.

The unreliability causes the system to require more cores to output the same quantity of refurbished products. Hence, the increase in IRDC size.

3. For d^R_{mk} = 16,000, the value of profit decreases with an increase in γ_p. It then increases and reaches a maximum value at $\gamma_p = 0.4$ and finally decreases. The decrease is due to the purchase of new parts to replace the poor quality parts in the system. The decrease also occurs due to increase in the number of IRDCs or opening of larger size IRDCs caused by the saturation in disassembly/inspection capacity of previously opened IRDCs. Similar trends can be seen for d^R_{mk} around 20,000 to 30,000 units.

4. For higher values of d^R_{mk} such as 100,000 units and with d^R_{mk} being greater than d_{mk}, the profit function decreases continuously due to high lost sales.

Sub-figure 3.10c obtained at d^R_{mk} = 16,000 illustrates the most general behaviour of the profit function when γ_p varies. The other sub-figures are subsets or special cases of sub-figure 3.10c. The general behaviour exhibits 4 phases:

- Initial dip (The first dotted line is placed at this point) in the graphs is due to the opening of an IRDC. As the quality of the products is reduced (γ_p increases), more products need to be disassembled and hence larger IRDCs are required which may cause localized slowdown in profit increase rate.

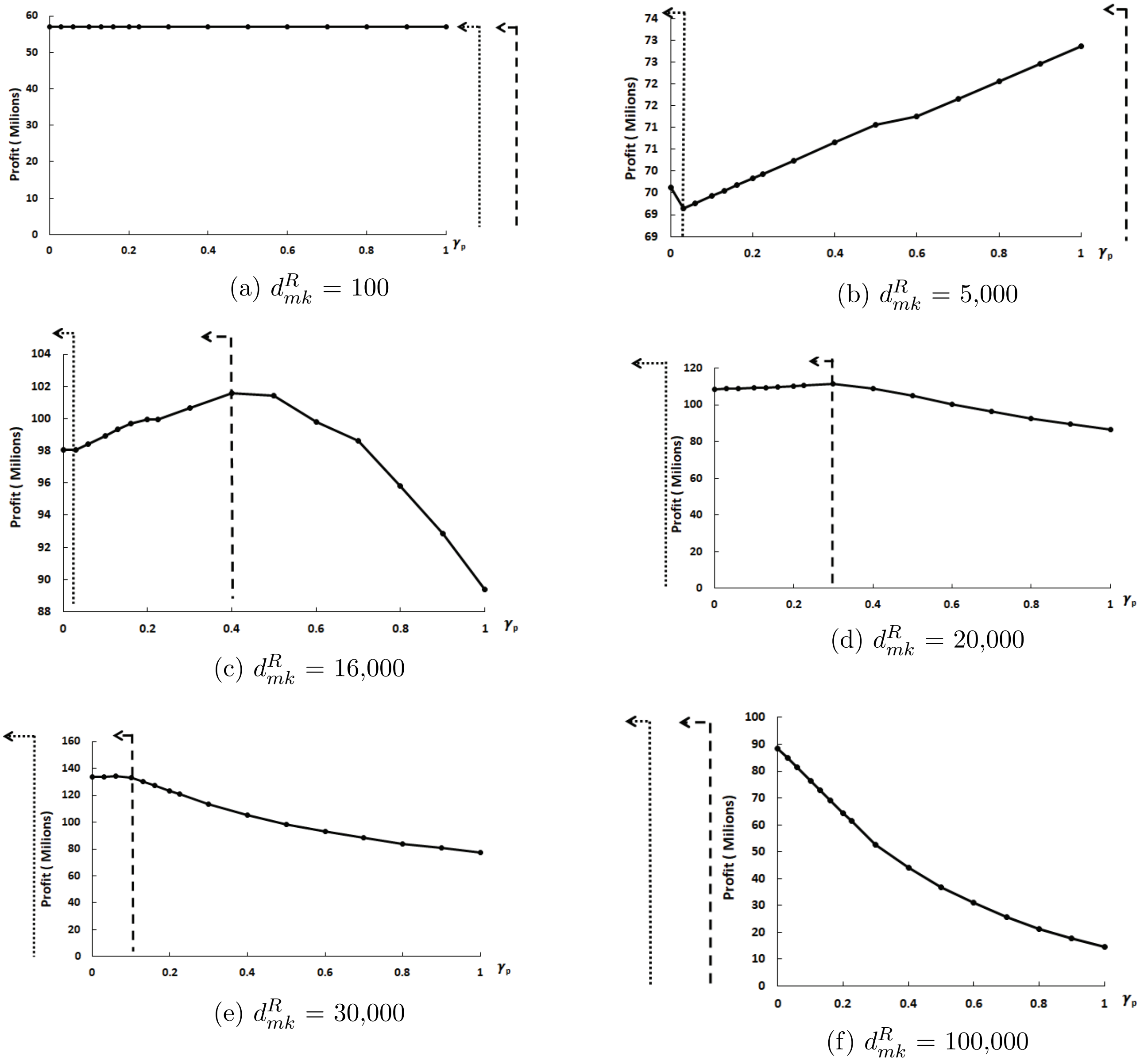
- The profit curves increase after the initial dip as parts required for the production of refurbished products are provided by disassembled parts and there is no need to purchase more expensive new parts from external suppliers. During this phase, the quantity of products disassembled and quantity of parts recovered from disassembly increase whereas no new parts are purchased.

- At a certain value of γ_p, the profit curve reaches a peak (a second dotted line is placed at this point) and then decreases. The peak occurs when the IRDCs are utilized at their full capacity and excess returned products are recycled.

- The decrease is due to a combination of several factors: the purchase of new parts to replace the poor quality of parts in the system, the increase in the number of IRDCs or opening of larger size IRDCs due to saturation in disassembly/inspection capacity of previously opened IRDCs.

We can see that both dotted lines move from the right to the left as d_{mk}^{R} increases.

Figure 3.10: Effects of variation of γ_p on profit under different scenarios of d_{mk}^{R}



(a) $d_{mk}^{R} = 100$

(b) $d_{mk}^{R} = 5{,}000$

(c) $d_{mk}^{R} = 16{,}000$

(d) $d_{mk}^{R} = 20{,}000$

(e) $d_{mk}^{R} = 30{,}000$

(f) $d_{mk}^{R} = 100{,}000$

3.6 Conclusion and future work

In this research, we modeled a CLSC network consisting of suppliers, CZs, IRDCs and a recycling centre with true multi-component products. The main contributions of this work are in studying the effects of economies of scale in locating IRDCs, transshipment of inspected products between IRDCs and part reliability on CLSC design.

Based on the experiments, we reached the following conclusions for the example network:

- CLSC networks with EOS generate a greater profit as compared to models without EOS. Difference in profit between the model with EOS and the model without EOS increases with increase in demand for refurbished products. Larger and fewer IRDCs are opened in the presence of EOS.

- The opening of fewer and larger sized IRDCs may result in excess or less inspection/disassembly capacity at different IRDCs locations. Transshipment of inspected products between IRDCs assists in balancing out these IRDC capacity constraints. Transshipment cost and disassembly capacity of the IRDC play a key role in deciding if the network can take advantage of transshipment. The difference in profit between a model with transshipment and one without transshipment increases as the quantities transshipped increases and the difference in profit decreases with a decrease in quantity transshipped. A large difference in profit is achieved in the case of low transshipment costs and high IRDC disassembly capacities. Low transshipment costs and low IRDC disassembly capacity imply transshipment at lower demand for refurbished products. Very high transshipment costs reduce the possibility of transshipment.

- The effect of part reliability on network profit depends on demand for refurbished products. Part reliability has little effect on network profits at extremely low values of demand for refurbished products. When demand for refurbished products is greater than demand for new products, then with increasing part unreliability the profit function keeps decreasing due to lost sales of refurbished products. For intermediate demand for refurbished products values, the profit function increases up to a maximum value as part unreliability increases. Beyond the maximum profit, the profit function decreases because parts acquired from disassembly operations are insufficient and the increase in the number of IRDCs or the opening of larger size IRDCs to overcome saturation in disassembly/inspection capacity of previously opened IRDCs incur additional fixed costs.

Future work can include a greater emphasis on part/product reliability, use concepts such as part failure rate from maintenance and reliability theory to model part reliability, use robust optimization or stochastic programming to model uncertainty in return part/product reliability, create multi-period models, and investigate the effects of dis-economies of scale.

CHAPTER 4

ROBUST CLSC DESIGN WITH PRE-SORTING AND CARBON EMISSION CONSIDERATIONS

4.1 Introduction

Governments are increasingly stepping up the pressure on organizations to recover their used products by creating directives such as Restriction on Hazardous Substances Restriction on Hazardous Substances (ROHS) and Waste Electrical Electronics Equipment Waste Electrical and Electronic Equipment (WEEE). These regulations have been passed to reduce the effects of manufacturing related activities on climate change (Abdallah et al., 2012). Closed loop supply chain management can assist organizations in abiding to and exceeding these new directives set out by governments (Bhattacharya and Kaur, 2015).

Products returns form a key input for the reverse supply chain and they have a variety of internal and external characteristics such as functionality, size, shape, product quality etc., which can vary depending on industry. The type of products received at collection centres may also vary. Certain collection centers receive only one type of product whereas others receive an assortment of products. For example, automotive recycling centers receive a smaller variety of products as compared to recycling centers for electronic equipment.

Returned products are collected and shipped to IRCs facilities. Returns with low residual value can be recycled directly from the collection centre to the recycling facility which results in fewer products being processed at IRCs, lower emissions and reduced expenditure in transporting returns to IRCs. Thus, early sorting procedures assist in capturing this low value returned products at the collection stage and can help reduce final recycling costs (Schultmann, Engels, and Rentz, 2003).

Quick sorting is another concept studied by researchers. Quick sorting has limited accuracy and can be achieved using small electronic devices built in products which analyze the number of work cycles the product has undergone. These devices provide information on remanufacturability of the product at the end of its life without the need to disassemble it (Zikopoulos and Tagaras, 2008).

CLSCs face a greater level of uncertainty as compared to the forward supply chain. Apart from the uncertainty in the products collected, CLSCs also face uncertainty in demand, price, cost and facility capacity. This uncertainty can create a crisis for supply chain managers. According to a Chinese proverb “CRISIS” is combination of danger and opportunity. Hence, if supply chain managers can prepare for uncertainties in the supply chain they can avert danger and reap hefty rewards from the hidden opportunities.

Demand uncertainty has received the greatest coverage from researchers, followed by return quantity and cost. Uncertainty in CLSCs can be overcome using fuzzy programming, stochastic programming, stochastic dynamic programming and RO (Safaei, Roozbeh, and Paydar, 2017). RO was found to be an effective technique as it provides optimal solutions when uncertain parameters are taken from a bounded uncertainty set (Ben-Tal and Nemirovski, 2008). For large scale problems, we do not need to know the exact distribution of the underlying data nor face computational difficulty as in stochastic programming (Pishvaee et al., 2011). These reasons make RO ideal for solving CLSC models with uncertainty.

Articles focus on incorporating RO in CLSC design in the automotive, cardboard recycling, engine oil, steel and electrical appliances industries. Robust CLSC models are primarily designed using single, bi-objective, or multi-objective MILP functions. Apart from considering objectives such as profit maximization and cost minimization, authors such as Mohammed, Selim, Hassan, and Syed (2017), Ameknassi, Aït-Kadi, and Rezg (2016) and Saffari, Makui, Mahmoodian, and Pishvaee (2015) focused on reducing carbon emissions during production, warehousing, disposal and reprocessing.

Industrial emissions have a negative impact on the environment and deteriorate the quality of life. The impact of emissions can be seen in cities such as Delhi, India and Beijing, China. Visibility is reduced to a few feet, people have a variety of respiratory problems and wear face masks daily. Realizing the hazardous impact of emissions, policy makers have developed emission reduction policies.
The three major emission policies implemented by governments are the carbon cap, carbon tax, and carbon cap and trade. In the carbon cap policy, the organization is permitted to emit a certain maximum amount of carbon emissions (Fareeduddin et al., 2015). In the carbon tax policy, organizations pay a tax for each unit of carbon emitted (Palak, Ekşioğlu, and Geunes, 2014).Whereas in the carbon cap and trade policy, there is a maximum threshold for the carbon emissions that can be generated. If the organization exceeds this carbon cap then they purchase carbon allowances from companies producing fewer emissions. On the other hand, if the company's emissions are lower than the carbon cap then they can sell carbon credits (Government of Ontario Website, 2018).

By implementing carbon reduction policies, the Government of Canada is trying to reduce the greenhouse gas emissions (GHGE) by 17 percent in the year 2020 as compared to emissions from the year 2005. Focus is on the transportation, electricity generation, and oil and gas sectors as they are the primary contributors to GHGE (Environment and climate change Canada Website, 2018).

Traditionally, authors in the literature focussed on minimizing the total cost of the CLSCnetwork. Authors incorporating emissions in CLSC, consider emissions during manufacturing (Chen, Wang, Wang, and Chen, 2017; Xu, Pokharel, Elomri, and Mutlu, 2017), warehousing (Tsao, Linh, Lu, and Yu, 2017), recycling (Chen et al., 2017) and transportation stages.

Ameknassi et al. (2016) model return quality uncertainty and achieving reduction in emissions in the CLSC by using stochastic multi-objective optimization. However, a gap in the literature is an extension considering pre-sorting as a strategy to triage returns. This paper addresses this gap by first presenting a deterministic MILP model for CLSC design considering multiple products, multiple CZs, quality of returns and the effects of emission policies (carbon cap, carbon tax, and carbon cap and trade). We also develop a robust version of the proposed deterministic model to study the impact of uncertain quality of returns on the behaviour of the network with pre-sorting centres.

The rest of the paper is organized as follows: Section 4.2 contains a literature review on sorting, RO and carbon emissions in CLSCs. Section 4.3 explains the framework of the CLSC network used in this paper; the proposed deterministic MILP model is presented in section 4.4. Numerical examples analyzing the behaviour of the proposed model are provided in section 4.5 . Section 4.6 proposes the robust extension of the deterministic model with uncertain product return quality. Section 4.7 describes experiments to test and characterize the robust model. Finally, section 4.8 contains the conclusion and possible future extensions.

4.2 Literature review

4.2.1 Sorting

While returns can usually be decomposed into multiple parts, most of the research in CLSC focus on individual parts. However, authors such as Bhattacharya and Kaur (2015); Abdallah et al. (2012); Toyasaki, Wakolbinger, and Kettinger (2013); Cardoso, Barbosa-Póvoa, and Relvas (2013); Özkır and Başlıgil (2013) considered multiple parts in their analysis.

Product characteristics such as length, mass, shape along with electromagnetic properties play a critical role during sorting. Special techniques like X-ray analysis and ultraviolet light are used to separate products such as batteries containing harmful chemicals (Schultmann et al., 2003). A variety of methods can be used for sorting. For example, Bhattacharya and Kaur (2015) consider the sorting of returned product based on quality grades while Gomes, Barbosa-Povoa, and Novais (2011) categorized products into 5 categories (large, small, cooling and refrigeration, lighting, monitors and television).

By studying the profitability of the system with and without sorting, Zikopoulos and Tagaras (2008) identified the conditions for sorting and suggested that its profitability depends on the cost and accuracy of sorting, quality of returned products and the costs associated with transportation, disposal and disassembly in the network.

Sorting can either occur at specialized collection centres, retailer locations or IRCs. Abdallah et al. (2012); Cardoso et al. (2013) assumed that retailers act as collection and sorting destinations whereas Bhattacharya and Kaur (2015), and Zikopoulos and Tagaras (2008) considered specialized collection facilities. Toyasaki et al. (2013) considered centralized and decentralized sorting facilities with EOS on return product acquisition costs. Zikopoulos and Tagaras (2008) used analytical expressions to determine whether sorting is beneficial before disassembly or before remanufacturing whereas Loomba and Nakashima (2012) studied the same problem used Markov decision process.

The following articles focussed on research on sorting in the automotive, personal computer, electrical and electronic equipment segments. Problems studied in literature address ambiguity in returns quality, location inventory decisions, lot size problems, CLSC design and product acquisition management.

Bhattacharya and Kaur (2015) studied a single period multi stage CLSC model using nonlinear optimization to overcome the uncertainty in the quality of returns. Network profit was maximized while simultaneously computing the selling price of products and quantity of returns entering different stages of the model. Applications in the automotive industry were elaborated upon.

Abdallah et al. (2012) studied the effects of quantity of returns, value of recovery, transportation and inventory costs on the centralization/decentralization of the supply chain by using a MINLP model. The model integrated the forward and reverse logistics loop to show their dependence on each other for location inventory decisions. To increase the recovery of products, a framework for allocating carbon credits to OEMs was also developed.

Using analytical solutions, Konstantaras, Skouri, and Jaber (2010) solved deterministic lot size problems where demand can be satisfied using new and recovered products. Policies for purchase of new products, inspection-sorting setup and techniques to determine optimal inventory levels of used items were also developed.

Toyasaki et al. (2013) used analytical models to find the role of information systems in CLSC and determined the conditions for eco-efficiency and profitability for organizations using game theory. The models developed have direct application for products which deteriorate in value and contain hazardous and precious materials (such as personal computers (PCs)).

Authors such as Schultmann et al. (2003); Cardoso et al. (2013); Özkır and Başlıgil (2013) incorporate sorting in CLSC design. Schultmann et al. (2003) developed an MILP model to replicate the CLSC network for battery recycling in the steel making industry using facility location and flow-sheeting-based process simulation. Based on the results obtained in this research, some smelters have started using spent batteries as raw material in their metallurgical operations.

On the other hand, Cardoso et al. (2013) used an MILP model to integrate forward and reverse supply chain to overcome uncertain demand by incorporating capacity expansions and flexible transportation links. Two scenarios were studied to overcome demand uncertainty: One where the network remains unaffected while demand scenarios change and the other where the transportation links adapt to the scenario.

Özkır and Başlıgil (2013) used fuzzy multi objective optimization to design a CLSC network to study uncertainty in product price and customer satisfaction level. The recovery network uses customer returned products, end-of-use and end-of-life goods to salvage materials, components and products. For a real-life problem, the model finds the optimal number and location of facilities in the network along with the quantities purchased, manufactured and transported.

Gomes et al. (2011) used an MILP model to design a network for recovering waste electric and electronic equipment in Portugal. The paper provides guidance on strategic decisions such as location of collection and sorting centres as well as assists in tactical decision making such as network planning.

The summary Table 4.1 classifies the articles on sorting based on various criteria such as number of periods, components, products and capacity of facilities.

4.2.2 Robust optimization and stochastic programming

RO and stochastic programming are used to deal with uncertainty in demand, return quality, return quantity, carbon emissions, facility capacity, etc. across a variety of industries including automotive, cardboard, petrochemicals and steel. RO techniques developed by Mulvey et al. (1995) and Ben-Tal and Nemirovski (1999) have been used extensively.

Mohammed et al. (2017) considered the effect of carbon policies such as carbon tax, carbon cap, carbon offset and carbon cap and trade on managerial decisions. They designed a CLSC for the automotive industry while incorporating uncertainty in the demand and return rate of products using stochastic scenarios. They also considered uncertainty in carbon emissions with a bounded box set leading to RO. Quantity of carbon emissions across the network and total supply chain costs are optimized and trade-offs between them are investigated.

Saffari et al. (2015) too considered reducing carbon emissions and network costs under conditions of uncertain customer demand. This was achieved using an MILP model incorporating mean and standard deviation of costs and solved by GA to achieve Pareto optimal solutions.

Table 4.1: Summary of papers on Sorting

Ref.	Method	Sorting	Settings								Problem solved	Industry examples
			Single Period	**Multi Period**	**Single component**	**Multi component**	**Single product**	**Multi product**	**Capacitated**	**Uncapacitated**		
Bhattacharya and Kaur (2015)	Nonlinear optimization	Products collected at collection centres from consumers and sorted based on quality. Acquisition price based on quality grade	*			*		*		*	Ambiguity in returns quality at the collection centre.	Automotive
Abdallah et al. (2012)	MINLP	Retailers collect and sort returned products				*	*			*	Models the relationship between the forward and the reverse loop in terms of location inventory decisions.	
Konstantaras et al. (2010)	Analytical solutions	Inspection and sorting procedures are combined, and a fixed and unit variable cost are introduced			*		*		*		Studies deterministic lot size problem where demand can be satisfied by new and recovered products	
Toyasaki et al. (2013)	Analytical models and numerical examples	Centralized and decentralized sorting facilities are modeled			*		*				Study of the role of information-intensive product recovery systems in CLSC	Personal computer
Schultmann et al. (2003)	MILP	Manual presorting followed by automatic presorting to separate batteries according to their chemical composition					*			*	Created a CLSC by combining facility location concepts and flow sheeting based process simulation	Recycling batteries in steel making

Table 4.2: Summary of papers on Sorting (continued)

Ref.	Method	Sorting	Settings								Problem solved	Industry examples
			Single Period	Multi Period	Single component	Multi component	Single product	Multi product	Capacitated	Uncapacitated		
Cardoso et al. (2013)	MILP	Retailers collect and sort returned products		*		*		*	*		Design and planning of an integrated forward and reverse supply chain facing demand uncertainty	European supply chain case study
Loomba and Nakashima (2012)	Markov decision process	Quick sorting products prior to disassembly and remanufacturing.		*	*		*				Improving product acquisition management under stochastically varying product quality levels.	Photocopier
Gomes et al. (2011)	MILP	At the sorting centre basic sorting activities classify products into large, small, cooling and refrigeration, monitors and televisions, and lighting.		*				*		*	Designing a recovery network for (Waste Electrical and Electronic Equipment) WEEE in Portugal	Electrical and Electronic Equipment
Özkır and Başlıgil (2013)	Fuzzy multi-objective optimization model	Inspection, sorting and recovery take place at the reverse centers		*		*		*	*		Setting up a CLSC network and recovery processes.	
Zikopoulos and Tagaras (2008)	Analytical expression	Quick sorting (limited accuracy) done at the collection site	*				*				Determine conditions under which quick sorting is justifiable	

Ameknassi et al. (2016) developed a bi-objective multi-period stochastic programming model to assist decision makers to analyze current network GHGE and outsourcing metrics before investing in low-carbon technologies. Uncertainty in consumer demand, return quality and quantity and facility capacity was incorporated using a scenario based approach. Several non-dominant supply chain configurations were provided by solving the model using the epsilon constraint method.

Safaei et al. (2017) solved a real-world problem in the cardboard recycling sector. They used MILP to model multiple suppliers, production units and implemented the method in Mulvey et al. (1995) to overcome demand uncertainty. The model maximized the network profit and calculated the optimal flow of waste paper into network and the cardboard output. To improve the current network, recyclers were advised to add an additional recycling facility to the network or consider overtime production at an existing facility. It was concluded that the profit in the network could further be increased by optimizing the waste collection process by collecting only recyclable paper.

Paydar, Babaveisi, and Safaei (2017) used the method in Mulvey and Ruszczyński (1995) method to overcome uncertainty in engine oil collection. Crude oil is an expensive and non-renewable raw material used in the production of engine oil. Used engine oil, if properly recycled, can attain qualities similar to new oils. The authors optimized an oil refinery network and used the augmented epsilon constraint method for profit maximization and collection risk minimization. It was found that product shortages can be decreased by increasing manufacturing centre capacities and a reliable supply of used oil can be achieved by selecting reputed suppliers via decision making analysis.

Most authors consider financial metrics to be exogenous variables but Ramezani, Kimiagari, and Karimi (2015) considered a different perspective to evaluate change in equity and maximize traditional profit. They used RO with the min-max approach to overcome demand and return rate uncertainty. Solutions were also obtained efficiently by employing a scenario relaxation algorithm.

The summary Table 4.3 classifies articles on various criteria such as robust and stochastic methods, number of periods, components, product, capacity of facilities, uncertain parameters, industry, problem solved and single/multi-objective.

4.2.3 Carbon emissions

Carbon emissions generated from constructing facilities, manufacturing, warehousing, handling and transportation activities has been covered across diverse industries. Most authors focus on cost minimization and reduction in emissions to make CLSC design environmentally friendly.

Chen et al. (2017) designed an integrated CLSC for the solar energy industry and developed a multi-objective model that optimized total costs and carbon emissions generated in the network. It was found that the proposed multi-objective particle swarm optimization (MOPSO) technique was superior to a branch and bound technique in solving large scale convoluted CLSC networks. The MOPSO technique with crowding distance based non-dominant sorting was used to find near optimal solutions.

Tsao et al. (2017) utilized a two-phase approach to design a CLSC taking into consideration remanufacturing and carbon emissions. In phase one, the forward loop is designed using a continuous approximation model and is solved using non-linear optimization. The total cost in the forward loop is minimized and the number, service area and replenishment time for distribution centres are found. Based on the results for the first phase, the number, service areas and replenishment time for remanufacturing facilities are found in the second stage. The model can solve big-data problems. Using numerical examples, the influence of costs associated with transportation, carbon emissions, demand rate, facilities and inventory holding on the network are studied.

Xu et al. (2017) researched the effects of carbon emissions on the design of a dedicated and hybrid CLSC. Impacts of emission policies (carbon cap, carbon cap and trade, and carbon tax) and market factors (customer demand, product return

Table 4.3: Summary of papers on two stage stochastic programming and robust optimization

Ref.	Methods	Robust Methods			Stochastic Methods	Settings					Uncertain Parameters				Industry	Problems	Single/Multi-objective
		Ben-Tal & Nemirovski	Mulvey / Yu & Li	Other		Single period	Multi period	Single Product	Multi product	Capacitated	Demand	Return Quality	Return quantity	Other			
Mohammed et al. (2017)	MILP	*		*	*		*		*	*	*		*	Carbon emissions	Automotive	CLSC network design	Single objective: minimize supply chain cost and carbon emissions
Safaei et al. (2017)	MILP		*				*	*		*	*				Cardboard	CLSC network design	Single objective: maximize supply chain profit
Paydar et al. (2017)	MILP		*				*		*	*			*		Engine oil	network design	Bi-objective: maximizing profit and minimizing collection risk
Ramezani et al. (2015)	MILP			*			*	*		*	*			Return rate		Integrating enterprise finance decisions and the physical flows of CLSC	Bi-objective: maximizing profit and change in equity
Saffari et al. (2015)	MILP		*			*		*		*	*				Steel	CLSC network design incorporating financial, social and environmental objectives	Multi-objective: minimizing cost and CO_2 emissions, enhancing job opportunities
Ameknassi et al. (2016)	MILNLP				*		*		*	*	*	*	*	Capacities of facilities , logistics variable costs.	Microwave oven	Integration of logistic outsourcing decisions while designing a green supply chain facing business uncertainty	Multi-objective: minimizing total logistic cost and CO_2 emissions

rate, scale effects) on CLSC design is investigated. It was found that the customer demand has a greater influence on total cost and network emissions as compared to the product return rate and scale effects. If the return quantities are uncertain then a dedicated CLSC is more economical. Also, dedicated CLSCs are more cost-efficient abiding to a carbon cap policy while hybrid CLSCs are more environmentally friendly under a carbon tax policy. The model provides examples from the plastic industry and can also be applied to networks in the aluminium and steel sectors.

Returnable transport items (RTI) are used for transporting products in the network as it reduces waste of disposable packaging. Sarkar, Ullah, and Kim (2017) developed a CLSC network for a hybrid manufacturing-remanufacturing system using RTI. The impact of not including transportation and carbon emission costs in the network are shown. Mathematical models not including these two costs risk of getting stuck at a local optimum. Apart from minimizing the transportation and emission costs, the number and capacity of containers, cycle time, shipping sequence and order quantity for retailers were also optimized by the model to find a suitable RTI management policy.

The summary Table 4.4 classifies articles on various criteria such as method and parameters to measure GHGE, modeling technique, settings, industry, problem solved and number of objectives (single/multi-objective).

4.3 Framework for CLSC network design with sorting and carbon emission considerations

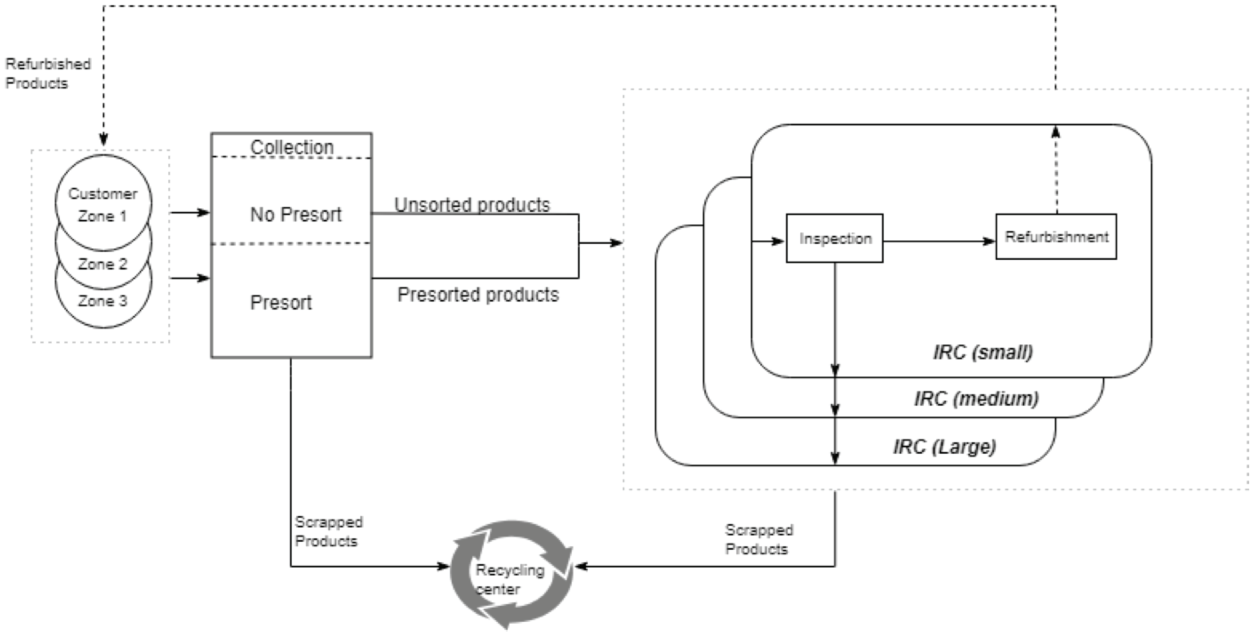
We consider a CLSC network comprising CZs, presorting centres, IRCs and a recycling centre as illustrated in Figure 4.1.

In the design problem, based on the quality and volume of returns at CZs, presorting centres may be established within them. If a presorting centre is present at a CZ, then good quality products and some poor quality products (depending on presorting efficiency) are sent to IRCs, while a majority of the poor quality products are

Table 4.4: Summary of papers on carbon emission

Ref.	Method and Parameters to measure GHGE	Method	Settings				Industry	Problem solved	Single/Multi-objective
			Single product	Multi product	Capacitated	Uncapacitated			
Chen et al. (2017)	Carbon emissions for 1) set up facilities such as production and recycling units 2) transportation 3) production of units	MILP	*		*		Solar cell	Design an Integrated CLSC with environmental and economic consideration	Multi-objective: minimize total cost and carbon emissions.
Tsao et al. (2017)	Carbon emissions for logistics and warehousing activities.	Nonlinear optimization	*			*		Two phase CLSC design considering remanufacturing and carbon cost.	single-objective: cost minimization
Xu et al. (2017)	Carbon emissions for transportation, handling the product and manufacturing parts.	MILP		*	*		Plastic	Studying the effects of carbon emissions in a dedicated and hybrid CLSC	single-objective: cost minimization
Sarkar et al. (2017)	1) Fixed emissions due to distances between network members, engine efficiency, emission per unit weight of fuel 2) Variable emission due to shipment weight	MINLP		*		*		Design of CLSC with 3PL	single-objective: cost minimization

Figure 4.1: Representation of the closed-loop supply chain network



identified during this stage and are directly sent to the recycling centre. The CLSC network becomes more streamlined as there are fewer bad quality products entering the IRC. The other decision choice is to send the products directly to the IRC without establishing a presorting centre at a CZ, e.g. when the quality of returns is very high. Several IRCs sizes may be considered at a location. At an IRC during inspection, bad quality products are sent to recycling while good quality products are refurbished. They are then sent from the IRC back to the CZs. By selling refurbished goods in the CZs the manufacturers try to generate a profit.

The assumptions used in the creation of the CLSC design model are:

- All refurbished products are sold at the CZs
- Location of CZs, and the recycling cente is predefined
- Presorting centres have unlimited processing capacity (this can be relaxed without difficulty).

4.4 CLSC design formulation with presorting under the carbon cap or cap and trade policies

In the carbon cap case, the maximum amount of carbon emissions in the network is constrained. In cap and trade, carbon emissions above the threshold are penalized, while total emissions below the threshold may be traded.

Transportation along the paths (CZs to the IRC and back, CZs to recycling and the IRC to recycling) and processes (collection, presorting, and inspection) generate emissions. These emission are penalized using a carbon emission cost to provide an incentive for emissions reduction. Processes such as refurbishment and recycling generate carbon credits in the network.

The following notation is used in the formulation of the CLSC network model for presorting centre choice, IRC size and product flows (both carbon cap and cap and trade are modeled using a binary parameter γ):

Indices

k	CZs
m	Products
s	IRC size

Parameters

β	Inefficiency of presorting, i.e. fraction of poor quality returns sent to the IRC from the presorting centres
c_{mk}^{1}	Unit transportation cost of product m from CZ k to IRC($ /Km-Kg)
$c1_{mk}^{R}$	Unit transportation cost of refurbished product m from IRC to CZ k ($/Km-Kg)
c_{mk}^{2}	Unit transportation cost of scrapped product m from CZ k to the RC($/Km-Kg)

c_m^3	Unit transportation cost of scrapped product m from IRC to the RC (\$/Km-Kg)
C_s	Inspection capacity of IRC of size s
CC	Carbon Cap (Kg of CO_2)
C_E	Carbon emission cost/ Carbon tax (\$/Kg of CO_2)
C_p	Penalty for exceeding carbon cap (\$/Kg of CO_2)
C_c	Credit for not exceeding carbon cap (\$/Kg of CO_2)
d	Distance between IRC and RC (Km)
d_k^1	Distance between CZ k and IRC (Km)
d_k^2	Distance between CZ k and RC (Km)
E	CO_2 emissions for transportation (Kg of CO_2/Kg-Km)
E_m^c	CO_2 emissions for collecting product m at CZs (Kg/unit)
E_m^i	CO_2 emissions for inspecting product m at IRC (Kg/unit)
E_m^p	CO_2 emissions for presorting product m at presorting facility (Kg/unit)
E_m^{ref}	Net CO_2 emissions for refurbishing product m at IRC (Kg/unit)
E_m^{rec}	Net CO_2 emissions for recycling products m (Kg/unit)
F_s	Fixed cost of opening IRC of size s
F_k^P	Fixed cost of opening presorting facility at CZ k.
I_m	Unit inspection cost of product m at IRC
P_{mk}	Unit presorting cost of product m at CZ k
R_m	Unit refurbishing cost of product m at IRC
RL_m	Unit recycling/landfilling cost of product m
S_{mk}	Selling price of refurbished product m in CZ k.
q_{mk}	Fraction of product m collected at CZ k of good quality
X_m	Weight of product m (Kg)
Z_{mk}	Quantity of product m collected at CZ k

$$\gamma = \begin{cases} 1 & \text{carbon cap and trade policy} \\ 0 & \text{carbon cap policy} \end{cases}$$

Decision variables

δ^{+}	Emissions above the carbon cap (Kg of CO_2), not required for carbon cap
δ^{-}	Emissions below the carbon cap (Kg of CO_2), not required for carbon cap
E^{P}	Total carbon emissions from processes (Kg of CO_2)
E^{T}	Total carbon emissions from transportation (Kg of CO_2)
$f1^{R}_{mk}$	Quantity of refurbished products m shipped from IRC to CZ k
f^{R}_{m}	Quantity of product m refurbished at IRC
f^{I}_{m}	Quantity of product m inspected at IRC
f^{2}_{mk}	Quantity of scrapped product m shipped from CZ k to recycling when presorting centre is present
f^{3}_{m}	Quantity of scrapped product m shipped from IRC to recycling
G_{mk}	Quantity of scrapped product m shipped from CZ k to recycling when presorting is absent
H_{mk}	Quantity of product m presorted
U_{mk}	Quantity of product m shipped from CZ k to IRC after Presort
V_{mk}	Quantity of product m shipped from CZ k to IRC without Presort

$$u_s = \begin{cases} 1 & \text{if IRCs of size } s \text{ is opened} \\ 0 & \text{otherwise} \end{cases}$$

$$Y_k = \begin{cases} 1 & \text{if presorting facility is opened at CZ } k \\ 0 & \text{otherwise} \end{cases}$$

The mathematical formulation for the maximization of total profit in the network is as follows:

Maximize Profit:

$$
\begin{aligned}
Z = & \sum_{m \in M} \sum_{k \in K} S_{mk} f1^{R}_{mk} - \sum_{s \in S} F_s u_s - \sum_{k \in K} F^{P}_{k} Y_k - \sum_{m \in M} \sum_{k \in K} d^{1}_{k} c^{1}_{mk} X_m f^{I}_{m} \\
- & \sum_{m \in M} \sum_{k \in K} d^{1}_{k} c1^{R}_{mk} X_m f1^{R}_{mk} - \sum_{m \in M} \sum_{k \in K} d^{2}_{k} c^{2}_{mk} X_m f^{2}_{mk} - \sum_{m \in M} \sum_{k \in K} d^{2}_{k} c^{2}_{mk} X_m G_{mk} \\
- & \sum_{m \in M} d c^{3}_{m} X_m f^{3}_{m} - \sum_{m \in M} \sum_{k \in K} P_{mk} H_{mk} - \sum_{m \in M} I_m f^{I}_{m} - \sum_{m \in M} R_m f^{R}_{m} \\
- & \sum_{m \in M} \sum_{k \in K} f^{2}_{mk} RL_m - \sum_{m \in M} \sum_{k \in K} G_{mk} RL_m - \sum_{m \in M} f^{3}_{m} RL_m - C_E \left(E^{T} + E^{P} \right) + \gamma \left(C_c \delta^{-} - C_p \delta^{+} \right)
\end{aligned}
\tag{4.1}
$$

Subject to:

$$Z_{mk} = G_{mk} + H_{mk} + V_{mk} \qquad \forall m, k \tag{4.2}$$

$$\sum_{m \in M} H_{mk} \leqslant Y_k \cdot \sum_{m \in M} Z_{mk} \qquad \forall k \tag{4.3}$$

$$U_{mk} = H_{mk} \left(q_{mk} + (1 - q_{mk}) \beta \right) \qquad \forall m, k \tag{4.4}$$

$$\sum_{m \in M} V_{mk} \leqslant C_3 \cdot (1 - Y_k) \qquad \forall k \tag{4.5}$$

$$(1 - \beta)(1 - q_{mk}) H_{mk} = f^2_{mk} \qquad \forall m, k \tag{4.6}$$

$$H_{mk} = f^2_{mk} + U_{mk} \qquad \forall m, k \tag{4.7}$$

$$f^I_m = \sum_{k \in K} U_{mk} + \sum_{k \in K} V_{mk} \qquad \forall m \tag{4.8}$$

$$f^R_m = f^I_m - f^3_m \qquad \forall m \tag{4.9}$$

$$f^3_m = \sum_{k \in K} (1 - q_{mk}) * V_{mk} + \sum_{k \in K} (1 - q_{mk}) \beta H_{mk} \qquad \forall m \tag{4.10}$$

$$f^R_m = \sum_{k \in K} f1^R_{mk} \qquad \forall m \tag{4.11}$$

$$\sum_{m \in M} f^I_m \leqslant \sum_{s \in S} C_s u_s \tag{4.12}$$

$$\sum_{s \in S} u_s \leqslant 1 \tag{4.13}$$

$$\begin{aligned} E^T = E \cdot \Big(& \sum_{k \in K} d^1_k \sum_{m \in M} U_{mk} X_m + \sum_{k \in K} d^1_k \sum_{m \in M} V_{mk} X_m \\ & + \sum_{k \in K} d^1_k \sum_{m \in M} f1^R_{mk} X_m + \sum_{k \in K} d^2_k \sum_{m \in M} f^2_{mk} X_m \\ & + \sum_{k \in K} d^2_k \sum_{m \in M} G_{mk} X_m + d \sum_{m \in M} f^3_m X_m \Big) \end{aligned} \tag{4.14}$$

$$\begin{aligned} E^P = & \sum_{m \in M} E^c_m \sum_{k \in K} Z_{mk} + \sum_{m \in M} E^p_m \sum_{k \in K} H_{mk} + \sum_{m \in M} E^i_m f^I_m \\ & - \sum_{m \in M} E^{ref}_m f^R_m - \sum_{m \in M} E^{rec}_m \sum_{k \in K} f^2_{mk} \\ & - \sum_{m \in M} E^{rec}_m f^3_m - \sum_{m \in M} E^{rec}_m \sum_{k \in K} G_{mk} \end{aligned} \tag{4.15}$$

$$E^T + E^P \leqslant CC + \gamma \left(\delta^+ - \delta^- \right) \tag{4.16}$$

$$f1^R_{mk}, f^R_m, f^I_m, G_{mk}, f^2_{mk}, f^3_m, E^T, E^P, H_{mk}, U_{mk}, V_{mk} \geqslant 0 \qquad \forall m, k \tag{4.17}$$

$$Y_k, u_s = \{0, 1\} \tag{4.18}$$

The objective (4.1) of the model is to maximize profit (revenue minus cost) for the CLSC network. The revenue is obtained by selling all the refurbished goods sent from the IRC to the CZs. Costs include the fixed cost of opening an IRC and presorting facilities, expenditures related to transportation, presorting, inspection, refurbishing, recycling, and carbon emission from transportation and processing. Quantity of emissions greater or less than the carbon cap also affects profit for the cap and trade policy.

Constraint (4.2) ensures flow balance at the CZ. Constraint (4.3) ensures that the quantity of products presorted will be less than the quantity of products collected. Constraint (4.4) determines the quantity of products sent from CZs to an IRC after presort. The flow consists of good quality products and a fraction of bad quality products due to presorting inefficiency. Constraint (4.5) ensures the quantity of products sent from CZs to the IRC in the absence of a presorting facility is less than the inspection capacity of the largest IRC. Constraint (4.6) determines the quantity of scrapped products sent from CZs to recycling centre after presorting. Constraint (4.7) creates a flow balance at the presorting facility. After presorting, a part of the products are sent to the recycling centre and the rest is shipped to the IRC. Constraint (4.8) determines the quantity of products inspected at the IRC, depending on the presence or absence of a presorting centre at the CZs. Constraint (4.9) ensures a flow balance at the IRC. Once a product is inspected at an IRC it can be refurbished or recycled. Constraint (4.10) determines the quantity of scrapped product sent from IRCs to recycling. The first term on the right of the equation calculates the number of bad products from the lot in the absence of presorting and the second term calculates the number of bad products from the lot in the presence of presorting. Constraint (4.11) ensures that all products refurbished at IRCs are delivered to the CZs. Constraint (4.12) is a capacity constraint on IRC inspection capacity. Constraint (4.13) ensures that only one size of IRC is opened. Constraint (4.14) determines the emission due to transportation in the network. Transportation from CZ to IRC, IRC to CZ and CZ to recycling in the presence and absence of presort and IRC to recycling is considered. Constraint (4.15) determines the emission due to various processes in the network. Processes such as product collection, presorting and inspection produce carbon emissions while refurbishing and recycling generate carbon credits. Constraint (4.16) ensures that emissions due to transportation and processes are less than the carbon cap for the carbon cap case. For cap and trade, this constraint calculates either the carbon deficit or excess. Constraint (4.17) and (4.18) enforce non-negativity and binary limitations on decision variables respectively. Flow variables are continuous while the opening/closing of pre-sorting or IRCs and choice of emission policy is governed by binary variables.

4.5 Model behaviour

The behaviour of the model is characterized using an example CLSC network with 3 CZs, 3 products and 3 IRC sizes (small, medium and large). Any one of the three sizes (small, medium or large) of IRCs can be established based on the quantity of products collected at the CZs and their quality. All models were implemented in GUSEK© (GLPK© Under Scite Extended Kit) 0.2 on an Intel(R)© Core i5-5250U CPU running at 1.6 GHz with 8.00 GB RAM. The parameters required for the model are listed in Tables 4.5 to 4.10.

Table 4.5: Fixed costs and inspection capacities for IRC of different sizes

IRC size (s)	C_s	F_s
Small	120,000	200,000
Medium	220,000	350,000
Large	300,000	500,000

Table 4.6: Selling price of refurbished product (S_{mk})

	CZs (k)		
Product (m)	1	2	3
1	200	200	200
2	300	300	300
3	250	250	250

To estimate the c^1_{mk} and $c1^R_{mk}$, package delivery using UPS services to send a package weighing 2.2lbs (1Kg) from Halifax, Ca (Postal code - B3H 4R2) to Truro, Ca (Postal code - B3N 5E3) are considered (UPS Website, 2018). The distance traveled is around 100 Km and the cost is $29.83. Hence unit transportation cost

Table 4.7: Distance between CZ and IRC, CZ and recycling centre

CZs	d_k^1	d_k^2
1	100	200
2	150	300
3	200	400

Table 4.8: Product recycling, inspection, refurbishment costs in $ and product weight in Kg.

Product (m)	RL_m	I_m	R_m	X_m
1	10	15	20	0.5
2	10	18	25	0.8
3	10	20	30	1.1

Table 4.9: Products collected at the CZ (Z_{mk})

	CZs (k)		
Product (m)	1	2	3
1	40,000	40,000	40,000
2	45,000	45,000	45,000
3	40,000	40,000	40,000

of the product is 0.2983 \$/Km-Kg. c^1_{mk} and $c1^R_{mk}$ are assumed to be 0.25 \$/Km-Kg, because the per Km cost reduces with distance and in the example the distances vary from 100–400 Km. c^2_{mk} and c^3_m are the unit costs of transporting scrapped products, and we chose 0.2 \$/Km-Kg, assuming they would be done in bulk.

Table 4.10: Parameters table

Parameter	Value
F^P_k	150,000
c^1_{mk}	0.25
$c1^R_{mk}$	0.25
c^2_{mk}	0.2
c^3_m	0.2
d	150
P_{mk}	10
q_{mk}	0 to 1
β	0 to 0.2
E^c_m	0.03
E^p_m	0.07
E^i_m	0.09
E^{ref}_m	0.21
E^{rec}_m	0.07
CC	30,000 for most experiments*
E	139.8 CO_2 emissions g/t Km (0.0001398 Kg/Kg Km)(European Environmental Agency)
C_E	\$18/t CO_2(\$0.018/Kg CO_2) Macleans (2018)
C_p	$C_p = 15*C_E$ Liu, Holmbom, Segerstedt, and Chen (2015), Hence C_p=15 * 0.018 = 0.27/Kg CO_2
C_c	0.5*C_p = 0.5*0.27 = 0.135/Kg CO_2 (assumption)

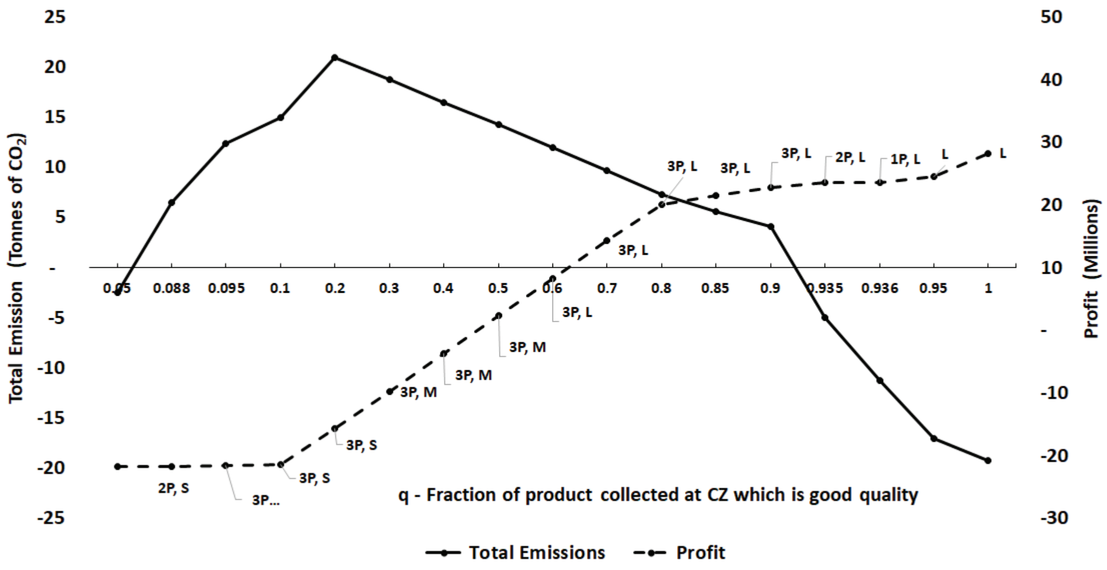
4.5.1 Experiment 1 - Investigating the impact of varying q_{mk} on total emissions and profit

In this experiment, the total CO_2 emissions and the profit from the network is calculated while changing the quality of returns (q_{mk}). A β value of 0.05 and CC value of 30,000 Kg of CO_2 were used for this experiment.

The number of presorting centres and the IRC sizes opened at different values of q_{mk} are given in Figure 4.2. The following notations are used in Figure 4.2: P - presorting centre, S - small IRC, M - medium IRC, L - large IRC.

As a result of the optimization, emissions due to processes increase from $q_{mk} = 0$ to $q_{mk} = 0.2$ and then decrease. For $q_{mk} = 0.05$, all products are sent directly from the CZ to the recycling centre. Recycling generates carbon credit for the network. But as q_{mk} increases to values near 0.1, fewer products are sent directly from the CZ

Figure 4.2: Effects of varying q on total emissions and profit



to the recycling centre. Since poor quality products proceed ahead in the network, more carbon emissions are generated and the maximum carbon emissions occur at $q_{mk} = 0.2$. As q_{mk} increases beyond 0.2, more products are refurbished and sold, resulting in lower carbon emission and increase in network profit. A positive profit is achieved when q_{mk} is greater than 0.461.

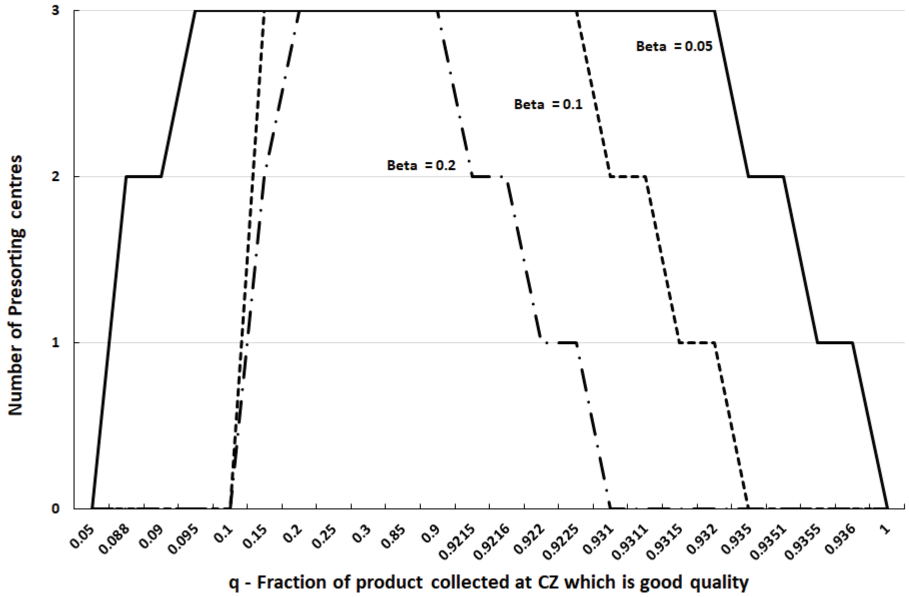
Thus, as q_{mk} increases, presorting centres are opened, fewer products are diverted from the CZ to the recycling centre and quantity of products sent to the IRC increases. Also, the IRC size increases with increasing q_{mk} and at high values of $q_{mk} \geq 0.935$, presorting centres start closing as all good quality returns are sent directly to the IRC.

4.5.2 Experiment 2 - Impact of presorting centre inefficiency (β) on opening of presorting centres

This experiment studies the impact of presorting centre inefficiency (β) on the opening of presorting centres. The number of presorting centres opened at different return quality levels (q_{mk}) are observed as β is varied (Figure 4.3). As can be seen, for any given value of β, presorting centres are first opened as quality increases and then start to get closed at very high quality. This is because presorting centres first come into play when products are worth recovering, but when the product quality is very high, they can be directly sent to the IRC.

From the experiment it can be seen that the range of presorting centre activities across quality levels is higher when the presorting inefficiency is low (e.g. $\beta = 0.05$). If presorting centres are more inefficient (e.g. $\beta = 0.2$), they are opened later (i.e at higher return quality) and closed earlier. In other words, efficient presorting centres are useful for a greater range of quality levels.

Figure 4.3: Impact of presorting centre inefficiency (β) on the opening of presorting centres for different q_{mk}



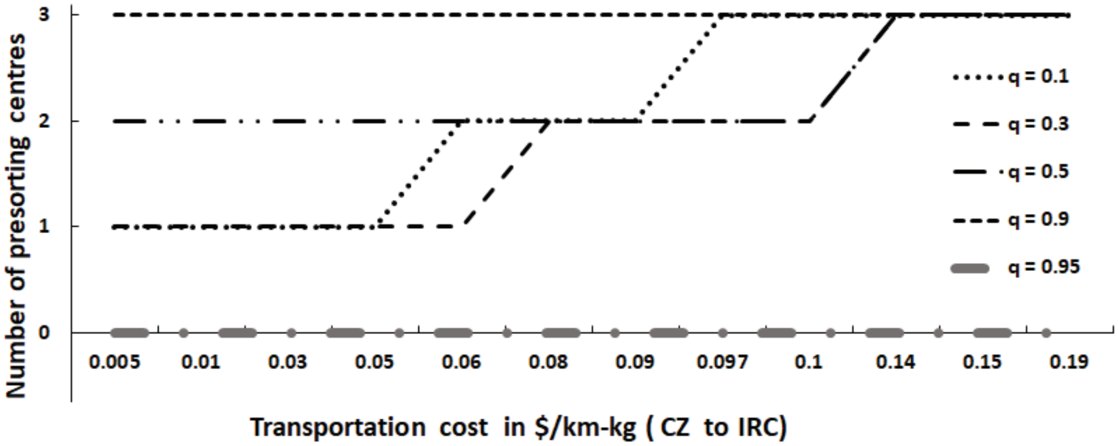
4.5.3 Experiment 3 - Impact of increasing transportation cost from CZs to the IRC (c^1_{mk}) on opening of presorting centres

This experiment studies the impact of increasing transportation cost from CZs to the IRC (c^1_{mk}) on the opening of presorting centres for different return quality levels (q_{mk}). $\beta = 0.1$ is for this experiment.

As seen in Figure 4.4, for a given return quality level, for low transportation costs few presorting centres are opened. As transportation costs increase, the number of presorting centres increase. More presorting centers are opened to prevent shipping large quantities of low quality products, which would be costlier as the transportation cost increases. In addition, as quality level increases, the presorting centre openings keep shifting to the top (until $q_{mk} = 0.9$). However, at very high return quality levels ($q_{mk} = 0.95$), no presorting centres are opened regardless of the transportation cost. In other words, there is a shift to the top followed by a sudden drop to the bottom.

For low transportation costs (i.e., $c^1_{mk} \leq 0.05$), the number of presorting centres opened is sensitive to the return quality levels. For high transportation costs (i.e., $c^1_{mk} \geq 0.14$), the solution is to open no presorting center for very high quality returns or open all presorting centres for the other return quality levels.

Figure 4.4: Impact of increasing transportation cost from CZs to IRCs (c^1_{mk}) on the opening of presorting centres for different q_{mk}



4.5.4 Experiment 4 - Comparison of carbon cap, cap and trade policies

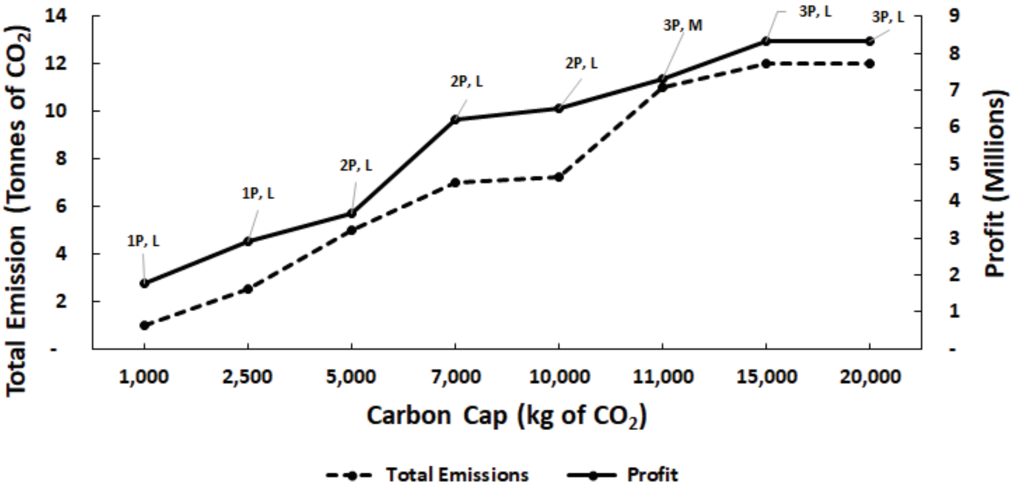
This experiment studies the effects of different carbon policies on the total carbon emissions produced and profit generated in the network. For this experiment the carbon cap is varied from 1,000 Kgs of CO_2 to 20,000 Kgs of CO_2 and a β of 0.05 is used.

- **Carbon Cap Policy**. As the carbon cap increases, the total emissions, total profit, and the number of presorting centres increase as seen in Figure 4.5.

Hence, there is structural change in the network while abiding to the carbon cap policy. The IRC size briefly switches from Large to Medium and back to large when the carbon cap changes from 10,000 to 11,000 and then back to 15,000. The behaviour is due to the opening of an additional presorting center which causes the volume of products shipped to the IRC to initialy decrease before increasing back.

- **Cap and Trade Policy**. The transportation emissions and process emissions remain constant for all variations in carbon cap. The profit function increase as the carbon cap increases as seen in Figure 4.7. 3 presorting centres and 1 large IRC were opened for all variations in carbon cap. Hence the network structure remained constant for the cap and trade policy. This difference in structural behaviour between these two policies was also observed by Mohammed et al. (2017).

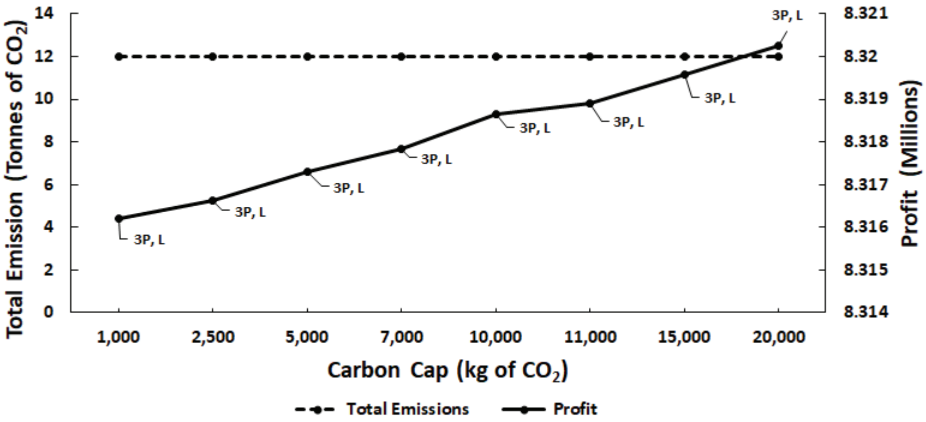
Figure 4.5: Emissions and profit for carbon cap policy



4.5.5 Experiment 5 - Investigating the effects of C_p on profit as the carbon cap changes

In the carbon cap and trade case, the effects of increasing C_p (penalty for exceeding carbon cap) are investigated. The general trend that can be seen from Figure 4.7 is

Figure 4.6: Emissions and profit for carbon cap and trade policy

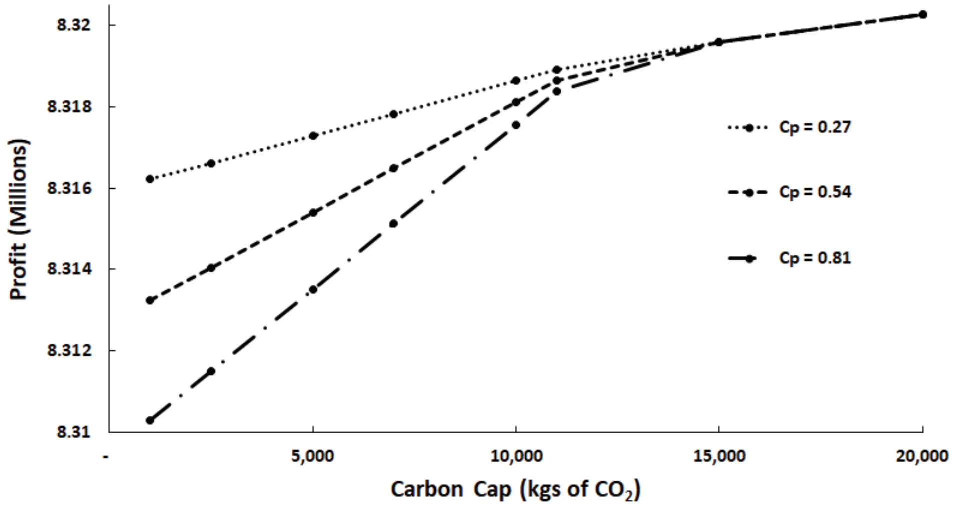


that the total profit increases sharply until a certain value of carbon cap (e.g., 11,000 Kgs of CO_2) and after that point the profit tends to increase at a slower pace. Below a carbon cap of 15,000 Kgs of CO_2, the network produces emissions greater than the carbon cap and hence higher the C_p, lower the profit. When the carbon cap is above 15,000 Kgs of CO_2, the amount of carbon emissions produced in the network is less than the carbon cap and the system is able to acquire carbon credits (C_c) for reduction in emissions. Hence if total carbon emissions are below the carbon cap, changing C_p will not affect the profit (i.e. all three curves overlap).

4.6 Robust model formulation

The deterministic model assumed a fixed value of return product quality, but in the real world the return product quality is uncertain. Uncertain return quality affects the quantity of returns to be processed. The CLSC network should have the flexibility to work with high or low volume of returns and at the same time keep network costs low. Strategic decisions such as establishing the right number of facilities with the right capacity is crucial under such circumstances. The right network structure can be achieved by reformulating the above deterministic model to deal with the uncertainty. From the literature review conducted in Chapter 2 above, it can be seen that robust optimization is one of the main techniques used by researchers to make

Figure 4.7: Effects of C_p on profit as the carbon cap changes



decisions under uncertainty. Hence, a robust model is developed to deal with the uncertainty in return quality in design of the CLSC with presorting.

The following notation is used in the formulation of the robust closed-loop supply chain network model:

Indices

k	CZs
m	Products
o	Scenarios
s	IRC size

Parameters

β	Inefficiency of presorting, i.e. fraction of poor quality returns sent to the IRC from the presorting centres
c_{mk}^1	Unit transportation cost of product m from CZ k to the IRC ($/Km-Kg)
$c1_{mk}^R$	Unit transportation cost of refurbished product m from IRC to CZ k ($/Km-Kg)

c^2_{mk}	Unit transportation cost of scrapped product m from CZ k to RC (\$/Km-Kg)
c^3_m	Unit transportation cost of scrapped product m from IRC to RC (\$/Km-Kg)
C_s	Inspection capacity of IRC of size s
CC	Carbon Cap (Kg of CO_2)
C_E	Carbon emission cost/ Carbon tax (\$/Kg of CO_2)
C_p	Penalty for exceeding carbon cap (\$/Kg of CO_2)
C_c	Credit for not exceeding carbon cap (\$/Kg of CO_2)
d	Distance between IRC and RC(Km)
d^1_k	Distance between CZ k and IRC (Km)
d^2_k	Distance between CZ k and RC (Km)
E	CO_2 emissions for transportation (Kg of CO_2/Kg-Km)
E^c_m	CO_2 emissions for collecting product m at CZ (Kg/unit)
E^p_m	CO_2 emissions for presorting product m at the presorting facility (Kg/unit)
E^i_m	CO_2 emissions for inspecting product m at IRC (Kg/unit)
E^{ref}_m	Net CO_2 emissions for refurbishing product m at IRC(Kg/unit)
E^{rec}_m	Net CO_2 emissions for recycling product m (Kg/unit)
F_s	Fixed cost of opening IRC of size s
F^P_k	Fixed cost of opening presorting facility at CZ k
I_m	Unit inspection cost of product m at IRC
M	Sufficiently large number
P_{mk}	Unit presorting cost of product m at CZ k
π	Penalty for exceeding inspection capacity of IRC
Pr_o	Probability of scenario o
q_{mko}	Fraction of good quality product m collected at CZ k under scenario o
R_m	Unit refurbishing cost of product m at IRC
RL_m	Unit recycling/landfilling cost of product m
S_{mk}	Selling price of refurbished product m in CZ k
X_m	Weight of product m (Kg)
Z_{mk}	Quantity of product m collected at CZ k

Decision variables based on scenario o

δ_o^+	Emissions above the carbon cap (Kg of CO_2)
δ_o^-	Emissions below the carbon cap (Kg of CO_2)
E_o^P	Total carbon emissions from processes (Kg of CO_2)
E_o^T	Total carbon emissions from transportation (Kg of CO_2)
$f1_{mko}^R$	Quantity of refurbished products m shipped from IRC to CZ k
f_{mo}^R	Quantity of product m refurbished at IRC
f_{mo}^I	Quantity of product m inspected at IRC
f_{mko}^2	Quantity of scrapped product m shipped from CZ k to recycling when presorting is present
f_{mo}^3	Quantity of scrapped product m shipped from IRC to recycling
G_{mko}	Quantity of scrapped product m shipped from CZ k to recycling when presorting is absent
H_{mko}	Quantity of product m presorted
ω_o^+	Quantity of products to be inspected exceeding the inspection capacity of IRC
ω_o^-	Slack or unused inspection capacity of IRC
U_{mko}	Quantity of product m shipped from CZ k to IRC after Presort
V_{mko}	Quantity of product m shipped from CZ k to IRC without Presort

$$u_s = \begin{cases} 1 & \text{if IRC of size } s \text{ is opened} \\ 0 & \text{otherwise} \end{cases}$$

$$Y_k = \begin{cases} 1 & \text{if presorting facility is opened at CZ } k \\ 0 & \text{otherwise} \end{cases}$$

The mathematical formulation for the maximization of total profit in the network is as follows:

Maximize Profit:

$$\begin{aligned}
Z = & \sum_{o\in O}\sum_{m\in M}\sum_{k\in K} Pr_o S_{mk} f1^R_{mko} - \sum_{s\in S} F_s u_s - \sum_{k\in K} F^P_k Y_k - \sum_{o\in O}\sum_{m\in M}\sum_{k\in K} Pr_o d^1_k c^1_{mk} X_m f^I_{mo} \\
- & \sum_{o\in O}\sum_{m\in M}\sum_{k\in K} Pr_o d^1_k c1^R_{mk} X_m f1^R_{mko} - \sum_{o\in O}\sum_{m\in M}\sum_{k\in K} Pr_o d^2_k c^2_{mk} X_m f^2_{mko} \\
- & \sum_{o\in O}\sum_{m\in M}\sum_{k\in K} Pr_o d^2_k c^2_{mk} X_m G_{mko} - \sum_{o\in O}\sum_{m\in M} Pr_o d c^3_m f^3_{mo} X_m - \sum_{o\in O}\sum_{m\in M}\sum_{k\in K} Pr_o P_{mk} H_{mko} \\
- & \sum_{o\in O}\sum_{m\in M} Pr_o I_m f^I_{mo} - \sum_{o\in O}\sum_{m\in M} Pr_o R_m f^R_{mo} - \sum_{o\in O}\sum_{m\in M}\sum_{k\in K} Pr_o f^2_{mko} RL_m \\
- & \sum_{o\in O}\sum_{m\in M}\sum_{k\in K} Pr_o G_{mko} RL_m - \sum_{o\in O}\sum_{m\in M} Pr_o f^3_{mo} RL_m - C_E \sum_{o\in O} Pr_o \left(E^T_o + E^P_o\right) \\
- & \sum_{o\in O} Pr_o C_p \delta^+_o + \sum_{o\in O} Pr_o C_c \delta^-_o - \sum_{o\in O} Pr_o \pi \omega^+_o
\end{aligned} \tag{4.19}$$

Subject to:

$$Z_{mk} = G_{mko} + H_{mko} + V_{mko} \qquad \forall m,k,o \quad (4.20)$$

$$\sum_{m\in M} H_{mko} \leqslant Y_k \sum_{m\in M} Z_{mk} \qquad \forall k,o \quad (4.21)$$

$$U_{mko} = H_{mko}\left(q_{mko} + (1-q_{mko})\,\beta\right) \qquad \forall m,k,o \quad (4.22)$$

$$\sum_{m\in M} V_{mko} \leqslant C_3(1-Y_k) \qquad \forall k,o \quad (4.23)$$

$$(1-\beta)(1-q_{mko})H_{mko} = f^2_{mko} \qquad \forall m,k,o \quad (4.24)$$

$$H_{mko} = f^2_{mko} + U_{mko} \qquad \forall m,k,o \quad (4.25)$$

$$f^I_{mo} = \sum_{k\in K} U_{mko} + \sum_{k\in K} V_{mko} \qquad \forall m,o \quad (4.26)$$

$$f^R_{mo} = f^I_{mo} - f^3_{mo} \qquad \forall m,o \quad (4.27)$$

$$f^3_{mo} = \sum_{k\in K}(1-q_{mko})V_{mko} + \sum_{k\in K}(1-q_{mko})\beta H_{mko} \qquad \forall m,o \quad (4.28)$$

$$f^R_{mo} = \sum_{k\in K} f1^R_{mko} \qquad \forall m,o \quad (4.29)$$

$$\sum_{m\in M} f^I_{mo} = \sum_{s\in S} C_s u_s + \omega^+_o - \omega^-_o \qquad \forall o \quad (4.30)$$

$$f^I_{mo} \leqslant M \sum_{s\in S} u_s \qquad \forall m,o \quad (4.31)$$

$$\sum_{s\in S} u_s \leqslant 1 \qquad (4.32)$$

$$\begin{aligned} E^T_o = E\cdot\Big(&\sum_{k\in K} d^1_k \sum_{m\in M} U_{mko}X_m + \sum_{k\in K} d^1_k \sum_{m\in M} V_{mko}X_m \\ &+ \sum_{k\in K} d^1_k \sum_{m\in M} f1^R_{mko}X_m + \sum_{k\in K} d^2_k \sum_{m\in M} f^2_{mko}X_m \\ &+ \sum_{k\in K} d^2_k \sum_{m\in M} G_{mko}X_m + d\sum_{m\in M} f^3_{mo}X_m\Big) \end{aligned} \qquad \forall o \quad (4.33)$$

$$\begin{aligned} E^P_o = &\sum_{m\in M} E^c_m \sum_{k\in K} Z_{mk} + \sum_{m\in M} E^p_m \sum_{k\in K} H_{mko} + \sum_{m\in M} E^i_m f^I_{m,o} \\ &- \sum_{m\in M} E^{ref}_m f^R_{mo} - \sum_{m\in M} E^{rec}_m \sum_{k\in K} f^2_{mko} - \sum_{m\in M} E^{rec}_m f^3_{mo} \\ &- \sum_{m\in M} E^{rec}_m \sum_{k\in K} G_{mko} \end{aligned} \qquad \forall o \quad (4.34)$$

$$E^T_o + E^P_o = CC + \delta^+_o - \delta^-_o \qquad \forall o \quad (4.35)$$

$$\begin{aligned} &f1^R_{mko}, f^R_{mo}, f^I_{m,o}, G_{mko}, f^2_{mko}, f^3_{mo}, H_{mko}, U_{mko}, \\ &\qquad V_{mko}, E^T_o, E^P_o, \delta^+_o, \delta^-_o, \omega^+_o, \omega^-_o \geqslant 0 \end{aligned} \qquad \forall m,k,o \quad (4.36)$$

$$Y_k, u_s = \{0, 1\} \tag{4.37}$$

The return quality q_{mk} varies from one returned product to another. Thus, the corresponding parameter is made to depend on the potential return quality scenarios that could occur (i.e., q_{mk} becomes q_{mko}). There is a probability Pr_o associated with each scenario. The return quality has a direct impact on the quantity of products shipped to the IRC and inspected there. Therefore, two new variables ω_o^+ and ω_o^- are added to the model to represent the surplus or slack inspection capacity needed or not used respectively. A penalty for exceeding inspection capacity of the IRC (π) is added to the model. All continuous variables from the previous deterministic model are present in the robust model and are scenario dependent.

The objective function (4.19) structure remains the same as the objective function of the deterministic model (4.1) with the addition of probabilities associated with each term which are scenario dependent. The objective function includes terms to penalize the quantity of products which exceed the inspection capacity of the IRC.

Constraints (4.2) to (4.18) from the deterministic model are used here with variables modified to show scenario dependence. The main changes are as follows : Constraint (4.30) permits greater quantity of products to be inspected than the inspection capacity of the IRC. Constraint (4.31) ensures that an IRC size is selected before any product flow can be received for inspection. Constraint (4.35) permits transportation and processs emissions to exceed the carbon cap.

4.7 Robust model behaviour

The behaviour of the robust model is characterized using an example CLSC network with 3 CZs, 3 products and 3 IRC sizes (small, medium and large). Any one of the three sizes (small, medium or large) of IRCs can be established based on the quantity of products collected at the CZs and their quality. All models were implemented in GUSEK© (GLPK© Under Scite Extended Kit) 0.2 on an Intel(R)© Core i5-5250U CPU running at 1.6 GHz with 8.00 GB RAM. The parameters required for the model are listed in Tables 4.5 to 4.10 with some exceptions such as CC = 16,000 Kg of CO_2 and others given below.

4.7.1 Experiment 1 - Investigating impact of varying return quality (q_{mko}) on the network structure, total emissions and profit of the CLSC network

In this experiment, we consider different scenarios for q_{mko}. The parameter q_{mko} takes one of the three following values: 0.2 (low quality), 0.5 (medium) and 0.9 (high quality). Different scenarios are generated by varying the probability associated with each quality level. 12 quality scenarios are generated for this experiment. As seen in Table 4.11, as we move from scenario 1 to scenario 12 the probability associated with higher q_{mko} is increased.

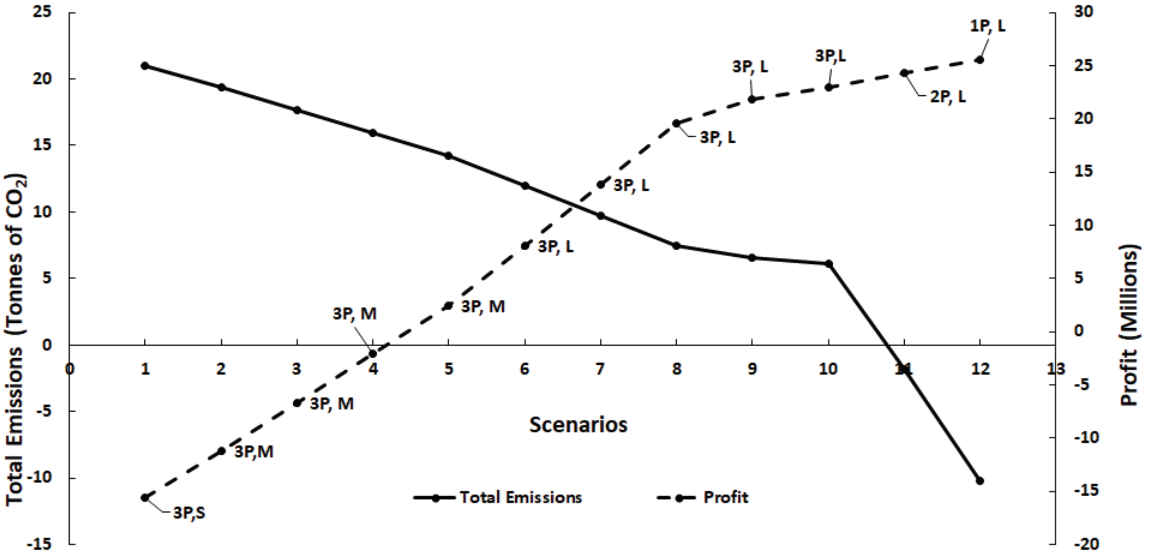
Table 4.11: Effect of varying return quality (q_{mko}) on the structure, total emissions and profit of the CLSC network

Scenario	1	2	3	4	5	6	7	8	9	10	11	12
q_{mko}	Probability of each quality											
0.2	1.00	0.75	0.50	0.25	-	-	-	-	-	-	-	-
0.5	-	0.25	0.50	0.75	1.00	0.75	0.50	0.25	0.15	0.10	0.05	-
0.9	-	-	-	-	-	0.25	0.50	0.75	0.85	0.90	0.95	1.00

Figure 4.8 displays the profit, emissions, number of presorting centres and the IRC size opened for different scenarios. The following notations are used in Figure 4.8: P - presorting centre, S - small IRC, M - medium IRC, L - large IRC.

As the probability of getting better quality returns increases, the total profit increases while the total carbon emissions decrease. Higher return quality also results in a steep change in the slope of the emissions curve from scenario 10 to scenario 11 as the system transitions from generating carbon emissions to acquiring carbon credits. The change in network structure is similar to experiment 4.5.1 of the deterministic model. There are more presorting centres and smaller IRCs for initial scenarios when product quality is low. While there are fewer presorting centres and larger IRCs for scenarios with high quality returns.

Figure 4.8: Effect of varying return quality (q_{mko}) on the structure, total emissions and profit of the CLSC network



4.7.2 Experiment 2 - Impact of varying π on the structure of the CLSC network

Under scenarios with high probability of good quality returns, the quantity of products shipped from CZ to the IRC may exceed its inspection capacity. When this happens, a penalty cost is incurred. In this experiment, we study the effects of varying the unit penalty cost for exceeding inspection capacity of IRC (π).

Table 4.12: Return quality scenarios to study effects of varying π on the structure of the CLSC network

Scenario	A	B	C	D
q_{mko}	Probability of quality			
0.2	0	0.05	0	0.33
0.5	0	0	0.05	0.33
0.9	1	0.95	0.95	0.34

We consider 4 scenarios with different probabilities for the 3 return quality levels as seen in Table 4.12 such that overcapacity can occur. Scenarios A, B, and C have

very low probability of poor quality returns, while scenario D is the equiprobable case. Table 4.13 displays the number of presorting centres opened and the IRC size for different scenarios under various values of π. In general, the number of presorting centres opened increase with π except for the equiprobable scenario where all presorting centers are always opened. Additional presorting centres are added to the network because these centres weed out the poor quality products at the very start of the CLSC network and fewer bad products reach the IRC. With fewer products being inspected at the IRC, the CLSC model achieves its objective of keeping the total quantity of inspected products below the inspection capacity of the IRC and reduces the impact of the increase in π.
It is also observed that the IRC size increases with π regardless of the scenario.

Table 4.13: Number of presorting centres opened and IRC size for different scenarios

	Scenarios			
π	A	B	C	D
1	0–S	0–S	1–S	3–S
5	0–L	0–L	1–L	3–M
15	0–L	1–L	1–L	3–L
30	1–L	2–L	2–L	3–L
50	2–L	3–L	3–L	3–L
100	3–L	3–L	3–L	3–L

4.7.3 Experiment 3 - Impact of increasing C_p on the network profit

In the robust model, the carbon emissions are permitted to exceed the carbon cap. But these excess emissions are penalized using C_p. The decision variable δ_o^+ indicates the amount of excess emissions. The scenarios (in Table 4.14) choosen for this experiment generate emissions greater than the carbon cap to show the impact of C_p on the profit of the network.

The obtained results are depicted in Table 4.15 and they showed that C_p has a direct impact on the network profit and an increase in C_p results in a proportional decrease in profit.

Table 4.14: Return quality scenarios used in experiment to study impact of increasing C_p on the network profit

Scenario	E	F	G
q_{mko}	Prob. of quality		
0.2	0.5	0.4	0.3
0.5	0.0	0.0	0.0
0.9	0.5	0.6	0.7

Table 4.15: Variation of network profit for increasing C_p (baseline at $C_p = 0.27$)

C_p		0.14	0.27	0.54	0.81	1.08
Scenario	E	326	0	-677	-1,353	-2,030
	F	261	0	-541	-1,082	-1,624
	G	195	0	-406	-812	-1,218

4.7.4 Experiment 4 - Comparison between robust and deterministic models

To compare both models, we run the robust model with equal probability (0.33) of occurrence for each of the 3 quality levels (i.e., $q_{mko} = 0.2,\ 0.5,\ 0.9$) while the deterministic model is run with the corresponding average of the 3 quality levels (i.e., $q_{mk} = 0.533$). We found that both the robust and deterministic models open 3 presorting centres. The deterministic model opened a medium sized IRC while the robust model opened a large IRC. By opening a large IRC the robust model has the ability to work with varying quality of returns. On the other hand, the deterministic model has limited ability to deal with varying quality of returns. The robust model has lesser profits as compared to the deterministic model. With emissions remaining nearly the same across both models. We can conclude that the robust model trades off a decrease in profit with the ability to deal with varying quality returns and ends up being more conservative.

Table 4.16: Comparing results of robust and deterministic model

	Robust	Deterministic
Presorting centres	3	3
IRC size	L	M
Profit	3,839,540	4,411,369
Total Emissions	13,501	13,508

4.8 Conclusion and future work

This chapter aimed to further research in CLSC design by incorporating pragmatic concepts such as varying return product quality, sorting and carbon emission policies in the proposed network model. MILP is used to develop the CLSC network model. CZs, pre-sorting centres, IRC and a recycling centre form the CLSC network. Refurbished products from the IRC are sold in the CZ thus generating new streams of revenue for the manufacturer while reducing the quantity of products sent to the landfill.

A deterministic model was first build to study the effect of varying return product quality on profit, carbon emissions and on the opening of pre-sorting facilities and IRCs. Effects of pre-sorting centre inefficiency and transportation cost between CZs and IRC on the opening of pre-sorting centres were investigated. The carbon cap policy was compared to the carbon cap and trade policy while focusing on structural change, network profit and emissions. For the cap and trade policy it was found that an increase in penalty for exceeding the carbon cap (C_p) resulted in a decrease in profit.

A robust model was then built and different scenarios for return quality were generated to study the effects of uncertainty in return quality on the network structure and profit, and emissions generated. We further studied the impact of exceeding inspection capacities and emission caps on the network structure and profit respectively. Finally, on comparing the deterministic model to the robust model we found the robust model to be more conservative, hedging against variation in return quality levels but less profitable. Possible future extensions can be to: a) use alternative RO approaches to solve the proposed model; b) focus on return quality, return quantity and collection stage uncertainty; and c) Develop multi-objective optimization models.

CHAPTER 5

CONCLUSIONS

The contributions of this thesis are in the areas of CLSC and RL. Companies are increasingly directing their efforts in these areas to both recapture economic benefit from used or returned products and materials and comply with environmental regulations. An additional incentive for companies is to improve their “green” image. This research work dealt with three themes: an extensive literature review on CLSC issues was conducted and presented in Chapter 2 followed by network modeling in Chapter 3 and 4 to address important considerations such as transshipment, economies of scale, presorting and uncertainty in returns quality. The conclusions and extensions for the 3 themes are given below.

5.1 Theme 1: Literature review

The first step in this research (Chapter 2) was to understand the state of the literature and identify gaps from a logistics or operations research (OR) perspective. We found the literature to be quite expansive and also rapidly changing. Therefore, we started with a review of review articles. We also narrowed the focus of the search on the following aspects of CLSCs and RL relevant to the objectives of this thesis:

1. Stochastic programming and robust optimization approaches to deal with uncertainties in the CLSC
2. Quality and reliability issues
3. Carbon emission models
4. Development of Greenness indices for a subsystem or the system as a whole

In each of the above areas, some gaps were discovered. For example, uncertainty in demand, return quantity and cost has received considerable coverage from researchers but uncertainty in return quality, price and capacity has not been covered as extensively. The robust optimization techniques applied in the literature are mainly based on the methods proposed in a few papers (Bertsimas and Sim, 2004a, 2003; Ben-Tal and Nemirovski, 2008, 1999; Ben-Tal et al., 2005; Ben-Tal and Nemirovski, 2000; Soyster, 1973; Mulvey et al., 1995) Robust techniques provide solutions which are pricier than those obtained from deterministic models as it creates solutions for all possible realizations of uncertain parameters.

From a functional perspective, a lot of emphasis has been placed on quality grading and quality pricing but there are very few publications incorporating the concept of reliability in CLSC.

Researchers have studied carbon emissions at the various stages of the CLSC and explored several emission related policies such as carbon cap, carbon tax, carbon cap-and-trade, e-commerce tax, and recycling subsidies, usually set by governments. These in turn imply carbon trading, carbon pricing strategies in CLSCs, consumer free riding behaviour, etc. Future works could build models integrating the emissions generated during product storage and handling, sales and product usage, and disposal. Additionally, it would be interesting to consider the types of energy utilized at each stage of the CLSC (renewable versus nonrenewable, fossil fuels, electric, hydrogen, etc.)

Greenness index models are developed using fuzzy methods, Analytical Hierarchy Process (AHP), Delphi method, grey relational analysis, balanced scorecard method, analytical network process, qualitative research methodologies and other techniques. Fuzzy based techniques are the one of the primary methodologies used for developing the greenness index. Authors should use more mathematical based methods such as preference function modeling (Barzilai, 2005) and other multicriteria aggregation functions.

5.2 Theme 2: Multicomponent multiproduct CLSC design with transshipment and economies of scale

With respect to CLSCs design, a gap in the literature is the effect of parts reliability on network configuration. When returned products or parts are highly reliable, IRDC capacity is lower because more products are available for refurbishing or for the recovery of parts through disassembly. However, when reliability is low, greater IRDC capacity is required. This can be achieved by either increasing their number or size. In the case of the latter, it was noted that EOS come into play. Since IRDCs are geographically dispersed in the supply chain, any network configuration model should allow for transshipment because when larger IRDCs are chosen as a result of EOS incentives, fewer of them are needed, which in turn implies transshipment between IRDCs. This very important gap in the literature was addressed in Chapter 3 where EOS, transshipment, and parts reliability in network configuration are considered. The behaviour of the model was characterized using example scenarios. In particular, it was concluded that:

1. With EOS, larger and fewer IRDCs are opened as compared to the case without EOS.
2. Network profit and presence of transshipment are affected by the transshipment cost between IRDCs and disassembly capacity of the IRDCs.
3. The effect of part reliability on network profit is complex and dependent on demand for refurbished products. This effect was characterized through detailed scenarios.

Future work could include a greater emphasis on part/product reliability, use concepts such as part failure rate from maintenance and reliability theory to model part reliability, use robust optimization or stochastic programming to model uncertainty in return part/product reliability, create multi-period models, investigate the effects of dis-economies of scale. In this research, we considered economies of scale for facility capacities and related costs but future works could consider economies of scale in other aspects of the supply chain, such as inventory, transportation etc.. Quantity discounts can also be considered on the purchase of new products from suppliers and/or on the sale of refurbished goods.

5.3 Theme 3: Robust CLSC design with pre-sorting and carbon emission considerations

From the literature review it was found that uncertainty in demand, return quantity and cost was extensively researched but uncertainty in return quality has received very little coverage, a theme addressed in Chapter 4. Low return quality reduces the number of usable returns and hence affects the strategic decision of establishing facilities with the right processing capacities. The problem of low return quality can be overcome by adding presorting centres in the network since costs associated with presorting are lower compared to the costs incurred at the IRCs. Moreover, the presorting centres can separate poor quality products at the start of the RL cycle and reduce transportation costs and emissions. A deterministic model to understand the effect of returns quality on the networks was proposed under the carbon cap case and cap and trade cases. Some of the conclusions from this analysis were:

1. Presorting centre efficiency and the transportation cost between CZ and the IRC determine the number of opened presorting centres.
2. As the return product quality improves, total emissions from the network decreases and profit increases.
3. In case of the carbon cap and trade policy, changing C_p (penalty for exceeding the carbon cap) affects the network profit only when carbon emissions exceed the carbon cap.
4. The carbon cap case affects network structure much more than cap and trade.

To model varying return quality, a robust CLSC model extension was developed. Return product quality was made scenario dependent in this formulation. This model was better able to deal with varying return quality. For poor quality returns, a larger number of presorting centres are opened and the IRCs is correspondingly smaller. Conversely, for high quality returns, a smaller number of presorting centres are opened and the IRCs is correspondingly larger. The robust model makes these trade-offs based on scenario probabilities.

Extensions could include: a) the use of alternative RO approaches to solve the proposed model; b) a joint focus on return quality, return quantity and collection stage uncertainty; c) the development of multi-objective optimization models.

All network models in this research focused on profit maximization, future work could focus on cost minimization. Network models could also consider multiple transportation modes between facilities, create provisions for disruptions, include customer service based metrics such as response time, taxes, and tariffs in the objective function. As supply chains are global in nature, we should also consider emissions generated by OEM suppliers, as much of the manufacturing process is outsourced. Developing networks where manufacturers of similar products collaborate in recycling initiatives can be beneficial to both manufacturers and society.

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APPENDIX A

GLPK codes for MILP models

For Chapter 3

Verification experiment. Section 3.5.1.
1) Opening of different sizes of IRDCs with the increase in demand for new products ($d_{m,k}$) while the demand for refurbished products ($d^R_{m,k}$) is kept constant at 100,000 units. Table 3.10. The following is the base models used for futher experiments

```
param part; #Number of part types
param product; #Number of products
param CZ; #Number of existing customer zones (CZ)
param IRDC; #Number of potential inspection, repaire and disassemble centers (IRDC)
param Size; # size of IRDC

set P, default (1..part); #Set of part types
set M, default (1..product); #Set of products
set K, default (1..CZ); #Set of existing customer zones (CZ)
set L, default (1..IRDC); #Set of potential inspection, repair and disassembly centers (IRDC)
set S, default (1..Size);#size of the IRDC

#Model Parameters
param Fl{l in L, s in S}; /*Fixed cost of opening IRDC l*/
param FlD{l in L,s in S}; /*Fixed cost of installing disassembly line in IRDC l*/
param pi{m in M}, >= 0; /*Assume linear purchasing cost of product m */
param cmk{m in M, k in K};  /*Shipping cost of new product m delivered to CZ k*/
param cmlk{m in M, l in L,k in K};  /*Shipping cost of repaired product m delivered from IRDC l to CZ k*/
param apl{p in P, l in L};  /*FOB destination cost of part p delivered to IRDC l*/
param cmkl{m in M, k in K, l in L};  /*Shipping cost per unit of product m from CZ k to IRDC l*/
param cml{m in M, l in L}, default 195;  /*Shipping cost per unit of scrapped product m from IRDC l to E-recycling center*/
param cmke{m in M, k in K}; /*Shipping cost per unit of returned product m  from CZ k to E-recycling*/
param cpl{p in P, l in L},default 5;  /*Shipping cost per unit of scrapped part p from IRDC l to E-recycling center*/
param I{m in M, l in L},default 10;  /*Inspection cost per unit of product m at IRDC l*/
param R{m in M, l in L};  /*Repair cost per unit of product m at IRDC l*/
param D{m in M, l in L};  /*Disassembly cost per unit of product m at IRDC l*/
param Cm{m in M};  /*Capacity for product m*/
param Cp{p in P};  /*Capacity for part p*/
param Cl{l in L,s in S};  /*Capacity of IRDC l for inspection*/
param ClD{l in L, s in S};  /*Capacity of IRDC l to disassemble product m*/
param d{m in M, k in K},default 150000;  /*Demand in customer zone k for new product m*/
param dR{m in M, k in K},default 100000;  /*Demand in customer zone k for repaired product m*/
param r{m in M,k in K};  /*Return rate of product m from CZ k*/
param gamma{p in P};  /*Fraction of part p requiring replacement for repair at IRDC*/
param sigma{p in P, m in M};  /*A binary parameter which shows if p is in product m or not*/
param theta{p in P};  /*Fraction of good parts of type p recovered from disassembly in IRDC*/
param rho{m in M, k in K}; /*Selling price of new product m in customer zone k*/
param rhoR{m in M, k in K};  /*Selling price of repaired product m in customer zone k*/
param eta{m in M, k in K}, >= 0; /*lost sale for unmet demand of repaired products*/
param tsc{m in M,l in L,l1 in L},default 10; /*Shipping cost per unit of product m from one IRDC  to another during transshipment*/

#Model Variables
var fml{m in M, l in L}, >= 0;/*Quantity of  products m inspected at IRDC l */
var fm{m in M}, >= 0;/*Related to demand for new  product m */
var fmk{m in M, k in K}, >= 0;/*Related to demand for new  product m in customer zone K */
```

```
var fmkl{m in M, k in K, l in L}, >=0;/*Quantity of products m  returned from customer zone k to IRDC l */

var fmlkR{m in M, l in L, k in K}, >=0;/*Quantity of refurbished products m sent from IRDC l to CZ k*/
var fpl{p in P, l in L}, >=0;/*Quantity of new part p shipped from suppliers to IRDC l*/
var gml{m in M, l in L}, >=0;/*Quantity of scrapped product m shipped from IRDC l to Recycling Center*/
var gpl{p in P, l in L}, >=0;/*Quantity of scrapped part p shipped from IRDC l to Recycling Centre*/
var omke{m in M, k in K}, >=0;/*Quantity of returned products m shipped from customer zone k to Recycling Centre*/
var deltaminus{m in M, k in K}, >= 0;/*Shortfall of refurbished products m in customer zone k*/
var fmlR{m in M, l in L}, >=0;/*Quantity of product m refurbished at IRDC l*/
var fmlD{m in M, l in L}, >=0;/*Quantity of product m disassembled at IRDC l*/
var Y{l in L, s in S}, binary;/*Related to opening of IRDC of size s at location l*/
var Z{l in L, s in S}, binary;/*Related to opening of disassembly line at location l  with size s */
var X{m in M,l in L,l1 in L},>=0;/*Quantity of product m transshipped  from l to l1*/

#Objective function
maximize Profit: (sum {m in M, k in K, l in L} rhoR[m,k]*fmlkR[m,l,k]
+ sum {m in M, k in K} rho[m,k]*fmk[m,k]
- sum {l in L, s in S} Fl[l,s]*Y[l,s]
- sum {l in L, s in S} FlD[l,s]*Z[l,s]
- sum {m in M} pi[m] * fm[m]
- sum {m in M, k in K} cmk[m,k]*fmk[m,k]
- sum {p in P, l in L} apl[p,l]*fpl[p,l]
- sum {m in M, l in L,k in K} cmlk[m,l,k]*fmlkR[m,l,k]
- sum {m in M, k in K, l in L} cmkl[m,k,l]*fmkl[m,k,l]
- sum {m in M, k in K} cmke[m,k]*omke[m,k]
- sum {m in M, l in L} cml[m,l]*gml[m,l]
- sum {p in P, l in L} cpl[p,l]*gpl[p,l]
- sum {m in M, k in K, l in L} I[m,l]*fmkl[m,k,l]
- sum {m in M, l in L} R[m,l]* fmlR[m,l]
- sum {m in M, l in L} D[m,l]* fmlD[m,l]
- sum{m in M, k in K} eta[m,k]*deltaminus[m,k]- sum{m in M,l in L,l1 in L:l1<>l}X[m,l,l1]*tsc[m,l,l1]);

#Constraints
#ensures that all products at IRDC  are inspected
s.t. definition_1{m in M, l in L}: sum{k in K} fmkl[m,k,l] = fml[m,l];

# Related to demand of new products
s.t. definition_2{m in M}: fm[m] = sum{k in K}fmk[m,k];

s.t. demand_satisfaction{m in M, k in K}: fmk[m,k] = d[m,k];


#  ensures that all refurbished products from the IRDC are sent to Customer zones.
s.t. IRDC_Balance_repaired_products{m in M, l in L}: fmlR[m,l] = sum{k in K} fmlkR[m,l,k];

#ensures that the total quantity of parts used in refurbishing activities is equal to the quantity of new parts
purchased from suppliers and like-new parts obtained from disassembly.
s.t. IRDC_Balance_Repaired_parts{p in P, l in L}: gamma[p]*sum{m in M} sigma[p,m]*fmlR[m,l] = fpl[p,l]+theta[p]*sum{m in M} sigma[p,m]*fmlD[m,l];

#ensures that scrapped parts from the disassembly process is sent to the recycling centre.
s.t. IRDC_Balance_scrapped_parts{p in P, l in L}: gpl[p,l] = (1-theta[p])*sum{m in M} sigma[p,m]*fmlD[m,l];

#  shows that lost sales are acceptable in case of refurbished products.
s.t. demand_satisfaction_for_repair{m in M, k in K}: sum{l in L} fmlkR[m,l,k] = dR[m,k] - deltaminus[m,k];

# ensures that all products returned from the Customer zone are either sent to the recycling centre or IRDC.
s.t. return_rate{m in M, k in K}: omke[m,k] + sum{l in L} fmkl[m,k,l] =r[m,k]*d[m,k];

#capacity constraints on the supplier capacity for new products
s.t. Capacity_supplier_product{m in M}: sum{k in K}fmk[m,k]<= Cm[m];

#capacity constraints on the supplier capacity for new parts
s.t. Capacity_supplier_part{p in P}: sum{l in L}fpl[p,l]<= Cp[p];
```

```
#capacity constraints on IRDC inspection capacity
s.t. Capacity_inspection{l in L}: sum{m in M} fml[m,l]<= sum{s in S} Cl[l,s]*Y[l,s];

##capacity constraints on IRDC disassembly capacity
s.t. Capacity_disassembly{l in L}: sum{m in M}fmlD[m,l] <= sum{s in S} ClD[l,s]*Z[l,s];

#ensures that only one IRDC of a specific size can be opened at a location.
s.t. Number_of_IRDCs_opened{l in L}:sum{s in S}Y[l,s]<=1;

#  ensures that a disassembly line is opened only when an IRDC is established.
s.t. IRDC_first{l in L, s in S}: Z[l,s] <= Y[l,s];

#  ensures flow balance at the~\glspl{IRDC}, with transshipment.  The RHS of the constraint sums up the number of products refurbished, disassembled, scrap
s.t. transshipment_balance_IRDC {m in M, l in L}: fmlR[m,l] + fmlD[m,l] + gml[m,l] + sum{l1 in L:l<>l1}X[m,l,l1] = fml[m,l] + sum{l1 in L:l<>l1}X[m,l1,l];

# ensures that the number of products transshipped is less than the number of products inspected at the IRDC
s.t. Receiving{m in M, l in L, l1 in L: l<>l1}: X[m,l,l1] <= fml[m,l];

solve;

display Profit,Y,Z, fmk,fml,fm,fmkl,fmlkR,fpl,gml,gpl,omke,deltaminus,fmlR,fmlD,X;

data;
param part :=3;
param product :=3;
param CZ :=3;
param IRDC :=3;
param Size :=3;#where 1,2,3 corresponds to small, medium and large IRDC respectively
param Fl :=
1 1 500000
1 2 800000
1 3 900000
2 1 500000
2 2 800000
2 3 900000
3 1 500000
3 2 800000
3 3 900000;

param FlD :=
1 1 1000000 #to prevent opening of disassembly lines for smaller IRDC's a large number is used
1 2 300000
1 3 400000
2 1 1000000 #to prevent opening of disassembly lines for smaller IRDC's a large number is used
2 2 300000
2 3 400000
3 1 1000000 #to prevent opening of disassembly lines for smaller IRDC's a large number is used
3 2 300000
3 3 400000;

param cmk :=
1 1 2
1 2 3
1 3 5
2 1 2
2 2 3
2 3 5
3 1 2
3 2 3
3 3 5;

param cmke :=
1 1 100
1 2 100
1 3 100
2 1 100
```

```
2 2 100
2 3 100
3 1 100
3 2 100
3 3 100;

param cmlk :=
1 1 1 2
1 1 2 3
1 1 3 4
2 1 1 2
2 1 2 3
2 1 3 4
3 1 1 2
3 1 2 3
3 1 3 4
1 2 1 2
1 2 2 3
1 2 3 4
2 2 1 2
2 2 2 3
2 2 3 4
3 2 1 2
3 2 2 3
3 2 3 4
1 3 1 2
1 3 2 3
1 3 3 4
2 3 1 2
2 3 2 3
2 3 3 4
3 3 1 2
3 3 2 3
3 3 3 4;

param apl :=
1 1 100
1 2 100
1 3 100
2 1 250/*standard cost is $100*/
2 2 250
2 3 250
3 1 100
3 2 100
3 3 100;

param cmkl :=
1 1 1 2
1 2 1 3
1 3 1 4
2 1 1 2
2 2 1 3
2 3 1 4
3 1 1 2
3 2 1 3
3 3 1 4
1 1 2 20
1 2 2 30
1 3 2 40
2 1 2 20
2 2 2 30
2 3 2 40
3 1 2 20
3 2 2 30
3 3 2 40
1 1 3 2
```

```
1 2 3 3
1 3 3 4
2 1 3 2
2 2 3 3
2 3 3 4
3 1 3 2
3 2 3 3
3 3 3 4;

param Cm :=
1 1000000
2 1000000
3 1000000;

param Cl :=
1 1 50000
1 2 100000
1 3 200000
2 1 50000
2 2 100000
2 3 200000
3 1 50000
3 2 100000
3 3 200000;

param Cp :=
1 100000
2 100000
3 100000;

param ClD :=
1 1 1
1 2 50000
1 3 100000
2 1 1
2 2 50000
2 3 100000
3 1 1
3 2 50000
3 3 100000;

param sigma :=
1 1 1
2 1 1
3 1 0
1 2 0
2 2 1
3 2 1
1 3 1
2 3 1
3 3 1;

param rhoR :=
1 1 250
1 2 250
1 3 250
2 1 250
2 2 250
2 3 250
3 1 250
3 2 250
3 3 250;

param eta :=
1 1 100
1 2 100
```

```
1 3 100
2 1 100
2 2 100
2 3 100
3 1 100
3 2 100
3 3 100;

param R :=
1 1 30
2 1 25
3 1 20
1 2 30
2 2 25
3 2 20
1 3 30
2 3 25
3 3 20;

param I :=
1 1 30
2 1 25
3 1 30
1 2 30
2 2 25
3 2 30
1 3 30
2 3 25
3 3 30;

param D :=
1 1 20
2 1 17
3 1 15
1 2 20
2 2 17
3 2 15
1 3 20
2 3 17
3 3 15;

param r:=
1 1 0.4
1 2 0.4
1 3 0.4
2 1 0.2
2 2 0.2
2 3 0.2
3 1 0.7
3 2 0.7
3 3 0.7;/* nt - affects the solution (cost) based on the demand of refurbished product 1/2/3 */

param pi :=
1 100
2 100
3 100;

param theta :=
1 0.4
2 0.5
3 0.6;

param gamma :=
1 0.5
2 0.5
3 0.5;
```

```
param rho :=
1 1 300
1 2 300
1 3 300
2 1 300
2 2 300
2 3 300
3 1 300
3 2 300
3 3 300;
end;
```

We use the same base model as before. Difference with respect to the base model are given for each experiment

---

For finding the economical operating range for reverse flow with EOS as seen in Figure 3.4 .
$d^R_{m,k}$ varies from 0 to 60,000 units and $d_{m,k}$ is 50,000 units.

Another verification experiment to investigate the effects of varying return rate ($r_{m,k}$) on the profit function as seen in Figure 3.5.
$d_{m,k}$ is 200,000 units, $d^R_{m,k}$ - 100,000 units and $r_{m,k}$ varies from 0 to 1.

The profit function is observed while changing the return rate for three different values of $d^R_{m,k}$ as seen in 3.6.
$d_{m,k}$ is 200,000 units, $d^R_{m,k}$ - 20,000/ 30,000/ 45,000 units and $r_{m,k}$ varies from 0 to 1.

For Experiment 3.5.2, for both with EOS and without EOS case $d_{m,k}$ is 90,000 units and $d^R_{m,k}$ varies from 0 to 30,000 units.
For the without EOS case the following changes also need to be done

```
param Fl :=
1 1 500000
1 2 1000000
1 3 2000000
2 1 500000
2 2 1000000
2 3 2000000
3 1 500000
3 2 1000000
3 3 2000000;
```

```
param FlD :=
1 1 1000000 #to prevent opening of disassembly lines for smaller IRDC’s a large number is used
1 2 300000
1 3 600000
2 1 1000000 #to prevent opening of disassembly lines for smaller IRDC’s a large number is used
2 2 300000
2 3 600000
3 1 1000000 #to prevent opening of disassembly lines for smaller IRDC’s a large number is used
3 2 300000
3 3 600000;
```

For Experiment 3.5.3, to achieve results as seen in Figure 3.8

For the transshipment and without transshipment case, $d_{m,k}$ is 300,000 units, $d^R_{m,k}$ changes from 0 to 100,000 units,with the following disassembly capacity changes

```
param ClD :=
1 1 1
1 2 25000
1 3 50000
2 1 1
2 2 25000
2 3 50000
3 1 1
3 2 25000
3 3 50000;
```

For only the transshipment case , transshipment cost between IRDCs ($T_{m,l,i}$) varies as 1/ 10/ 15 .

For without transshipment case, transshipment cost between IRDCs ($T_{m,l,i}$) and quantity transshipped ($X_{m,l,i}$) is absent. The following equation is removed

```
s.t. Receiving{m in M, l in L, l1 in L: l<>l1}: X[m,l,l1] <= fml[m,l];
```

The following equation

```
s.t. transshipment_balance_IRDC {m in M, l in L}:
fmlR[m,l] + fmlD[m,l] + gml[m,l] + sum{l1 in L:l<>l1}X[m,l,l1] =
fml[m,l] + sum{l1 in L:l<>l1}X[m,l1,l];
```

is modified to

```
s.t. transshipment_balance_IRDC {m in M, l in L}:
 fmlR[m,l] + fmlD[m,l] + gml[m,l]= fml[m,l] ;
```

For Experiment 3.5.3, to achieve results as seen in Figure 3.9 we include the above changes (used to achieve Figure 3.8) with transshipment cost is \$10 under different $C^D_{l,s}$ scenarios as seen in Table 3.12.

For Experiment 3.5.4, γ_p changes from 0 to 1, $d_{m,k}$ is 50,000 units, $d^R_{m,k}$ - 100/ 5,000/ 16,000/ 20,000/ 30,000/ 100,000 units and $r_{m,k}$ is 0.7

For Chapter 4

The deterministic model in section (4.4) used for Experiment 4.5.1 is given below. The value of return quality $q_{m,k}$ is varied from 0 to 1.

```
param product; #Number of products
param CZ; #Number of existing customer zones (CZ)
param Size;# size of IRC


set M, default (1..product); #Set of products
set K, default (1..CZ); #Set of existing customer zones (CZ)
set S, default (1..Size);#Size of IRCs


#Model Parameters
param FP{k in K}; /*Fixed cost of opening presorting facitlity at CZ k*/
param d1{k in K}; /*Distance between CZ k and IRC (km)*/
param d2{k in K}; /*Distance between CZ k and recycling centre (km) */
param d, default 150; /*Distance between IRC and recycling centre (km)*/
param c1{m in M, k in K}, default 0.25;/*unit transportation cost of product m from CZ k to IRC ($/km-kg) */
param c1R{m in M, k in K}, default 0.25;/*unit transportation cost of refurbished product m from IRC to CZ k($/km-kg) */
param c2{m in M, k in K}, default 0.2;/*unit transportation cost of scrapped product m from CZ k to recycling ($/km-kg) */
param c3{m in M}, default 0.2;/*unit transportation cost of scrapped product m from IRC to recycling ($/km-kg) */
param RL{m in M}, default 10;/*unit cost of recycling/landfilling product m */
param I{m in M};/*Inspection cost per unit of product m at IRC */
param R{m in M};/*Refurbishing cost per unit of product m at IRC*/
param P{m in M, k in K}, default 10;/* Presorting cost per unit of product m at CZ k*/
param q{m in M,k in K}, default 0.9; /*fraction of  product m collected at CZ k which is good quality */
param Z{m in M,k in K};/*quantity of product m collected  at CZ k*/
param Ec{m in M}, default 0.03;/*CO2 Emissions for collecting products at CZ (kg/unit)*/
param Ep{m in M}, default 0.07;/*CO2 Emissions for presorting products at CZ (kg/unit)*/
param Ei{m in M}, default 0.09;/*CO2 Emissions for inspecting products at IRC (kg/unit)*/
param Eref{m in M}, default 0.21;/* Net CO2  Emissions for refurbishing products at IRC (kg/unit)*/
param Erec{m in M}, default 0.07;/*Net CO2 Emissions for recycling products (kg/unit)*/
param E, default 0.0001398;/*CO2 Emissions for transportation (kg of co2/kg transported-km)*/
param X{m in M};/*product weight in kg*/
param CE, default 0.018;/*Carbon emission cost/ Carbon tax in $/kg of CO2*/
param beta, default 0.05;/*inefficiency at presort */
```

```
param price{m in M, k in K};/*Selling price of refurbished product*/
param F{s in S}; /*Fixed cost of opening IRC */
param C{s in S}; /*Inspection capacity of IRC*/
param CC, default 30000;/* Carbon cap in kg of CO2*/
param Cp, default 0.27; /*Penalty for exceeding carbon cap in $*/
param Cc, default 0.135; /*Credit for not exceeding carbon cap in $*/

#Model Variables
var fmkR{m in M, k in K}, >= 0;/*Quantity of refurbished product m sent from the IRC to CZ k*/
var fmR{m in M},>=0; /*quantity of product m refurbished at IRC*/
var fmI{m in M},>=0; /*quantity of product m inspected at IRC*/
var G{m in M, k in K}, >=0; /* quantity of scrapped product m sent from CZ k to recycling when "Presort is absent"*/
var f2{m in M, k in K},>=0;/*quantity of scrapped product m sent from CZ k to recycling _ Presort open */
var f3{m in M},>=0;/*quantity of scrapped product m sent from IRC  to recycling */
var Y{k in K}, binary;/*Opening and closing of presort*/
var u{s in S}, binary;/*IRC size*/
var ET, >=0; /*total carbon emissions from transportation*/
var EP; /*total carbon emissions from  processes*/
var deltaP ,  >= 0;/*Emissions greater than carbon cap stored in this variable*/
var deltaN ,  >= 0;/*Emissions lesser than carbon cap stored in this variable*/
var H{m in M, k in K},>=0;/*quantity of product presorted */
var U{m in M, k in K},>=0;/*Quantity of products sent from CZ  to IRC after Presort */
var V{m in M, k in K},>=0;/*Quantity of products sent from CZ  to IRC without Presort */

#Objective function
maximize Profit: sum {m in M, k in K}price[m,k]*fmkR[m,k]
- sum{s in S}F[s]*u[s]
- sum {k in K}FP[k]*Y[k]
- sum {m in M, k in K}d1[k]*c1[m,k]*X[m]*fmI[m]
- sum {m in M, k in K}d1[k]*c1R[m,k]*X[m]*fmkR[m,k]
- sum {m in M, k in K}d2[k]*c2[m,k]*X[m]*f2[m,k]
- sum {m in M, k in K}d2[k]*c2[m,k]*X[m]*G[m,k]
- sum {m in M}d*c3[m]*f3[m]*X[m]
- sum {m in M,k in K}P[m,k]*H[m,k]
- sum {m in M}I[m]*fmI[m]
- sum {m in M}R[m]*fmR[m]
- sum {m in M, k in K}f2[m,k]*RL[m]
- sum {m in M, k in K}G[m,k]*RL[m]
- sum {m in M}f3[m]*RL[m]
- CE*(ET+EP)- Cp*deltaP + Cc*deltaN;

#Flow balance at CZ
s.t. Flow_balance_at_CZ{m in M, k in K}:Z[m,k] = G[m,k] + H[m,k] + V[m,k];

#  ensures that the quantity of products presorted  will be less than the quantity of products collected
s.t. definition_H{k in K}:sum{m in M}H[m,k]<=Y[k]*sum{m in M}Z[m,k];

#Quantity of products sent from CZ  to IRC after Presort
s.t. Products_sent_to_IRC1{m in M, k in K}: U[m,k] = H[m,k]*(q[m,k]+ (1 - q[m,k])*beta);

#Quantity of products sent  from CZ to IRC  without presort
s.t. Products_sent_to_IRC2{k in K}: sum{m in M}V[m,k] <= C[3]*(1 - Y[k]);

# Quantity of scrapped products sent from CZ to recycling after presorting
s.t. Products_sent_from_CZ_to_recycling{m in M, k in K}:(1 - beta)*(1 - q[m,k])*H[m,k] = f2[m,k];

#Flow balance at Presort facility
s.t. Flow_balance_at_Presort{m in M, k in K}:H[m,k] = f2[m,k] + U[m,k];

# Total quantity inspected
s.t. Quantity_inspected{m in M}:fmI[m] = sum{k in K}U[m,k] + sum{k in K}V[m,k];

#  Flow balance at IRC
s.t. Product_from_Inspection_to_refurbishment{m in M}: fmR[m] = fmI[m] - f3[m];

# Quantity of scrapped products sent from IRC to recycling
```

```
s.t. Products_sent_from_IRC_to_recycling{m in M}: f3[m] = sum{k in K} (1-q[m,k])*V[m,k] + sum{k in K} (1-q[m,k])*beta*H[m,k];

#  ensures that all products refurbished at IRC are delivered to the CZ
s.t.Refurbished_product_balance{m in M}:fmR[m]=sum{k in K}fmkR[m,k];

# capacity of IRC
s.t. IRC_Capacity:sum{m in M}fmI[m] <= sum{s in S}C[s]*u[s];

# only one size of IRC is opened
s.t. IRC_size: sum{s in S} u[s]<=1;

#Total Carbon emissions from transportation
s.t. Emissions_from_Transportation:ET = (sum{k in K}d1[k]*(sum{m in M}U[m,k]*X[m]))*E
+(sum{k in K}d1[k]*(sum{m in M}V[m,k]*X[m]))*E
+(sum{k in K}d1[k]*(sum{m in M}fmkR[m,k]*X[m]))*E
+(sum{k in K}d2[k]*(sum{m in M}f2[m,k]*X[m]))*E
+(sum{k in K}d2[k]*(sum{m in M}G[m,k]*X[m]))*E
+(d*(sum{m in M}f3[m]*X[m]))*E;

#Total Carbon emissions from processes
s.t. Emissions_from_Processes:EP = sum{m in M}Ec[m]*(sum{k in K}Z[m,k])
+sum{m in M}Ep[m]*(sum{k in K}H[m,k])
+sum{m in M}Ei[m]*fmI[m]
-sum{m in M}Eref[m]*fmR[m]
-sum{m in M}Erec[m]*(sum{k in K}f2[m,k])
-sum{m in M}Erec[m]*f3[m]
-sum{m in M}Erec[m]*(sum{k in K}G[m,k]);

#)ensures that emissions due to transportation and processes are less than the carbon cap for the carbon cap case. For cap and trade, this constraint calcu
s.t. Carbon_cap_constraint:ET+EP <= CC + deltaP - deltaN;

#Carbon Cap and Trade case is the default case

#Carbon Cap case - Activate next two constraints.("Add less than sign in  above equation ")
 Deactivate for cap and trade. ("Remove less than sign in above equation ")

s.t. Carbon_cap_constraint1: deltaP = 0;
s.t. Carbon_cap_constraint2: deltaN = 0;

solve;

display Profit,fmkR,fmR,fmI,f2,f3,u,Y,G, ET, EP, deltaP, deltaN;

#,Part_Repair

data;

param product :=3;
param CZ :=3;
param Size :=3;

/*IRC fixed costs*/
param F:=
1 200000/*small*/
2 350000/*medium*/
3 500000;/*large*/


/*Inspection capacity of IRC*/
param C:=
1 120000
2 220000
3 300000;

/*Selling price of refurbished product*/
param price :=
```

```
1 1 200
1 2 200
1 3 200
2 1 300
2 2 300
2 3 300
3 1 250
3 2 250
3 3 250;

/*Fixed cost of opening presorting facitlity at CZ k*/
param FP :=
1 150000
2 150000
3 150000;

/*Distance between CZ k and IRC (km)*/
param d1 :=
1 100
2 150
3 200;

/*Distance between CZ k and recycling centre (km) */
param d2 :=
1 200
2 300
3 400;

/*Inspection cost per unit of product m at IRC */
param I :=
1 15
2 18
3 20;

/*Refurbishing cost per unit of product m at IRC*/
param R :=
1 20
2 25
3 30;

/*quantity of product m collected  at CZ k*/
param Z :=
1 1 40000
1 2 40000
1 3 40000
2 1 45000
2 2 45000
2 3 45000
3 1 40000
3 2 40000
3 3 40000;

/*product weight in kg*/
param X:=
1 0.5
2 0.8
3 1.1;

end;
```

The above deterministic model is used for futher experiments with changes given below.

For Experiment 4.5.2, as $q_{m,k}$ is varied from 0 to 1 , β is varied to 0.05/ 0.1/ 0.2 and the number of open presorting centres is noted.

For Experiment 4.5.3, $q_{m,k}$ is varied from 0.1 to 0.95 , β is constant at 0.1, $c^1_{m,k}$ is varied from 0.005 to 0.19 and the number of open presorting centres is noted.

For Experiment 4.5.4, for the carbon cap case, $q_{m,k}$ is constant at 0.6, carbon cap is varied from 1,000 to 20,0000 kgs of CO_2 . Profit and emissions are noted in this experiment.

The robust model in section (4.6) used for Experiment 4.7.1 is given below. Return quality scenarios are given in Table 4.11.

```
param product; #Number of products
param CZ; #Number of existing customer zones (CZ)
param Size;# size of IRC
param Scenario;# Number of scenarios

set M, default (1..product); #Set of products
set K, default (1..CZ); #Set of existing customer zones (CZ)
set S, default (1..Size);#Size of IRCs
set O, default (1..Scenario);#Scenarios

#Model Parameters
param FP{k in K}; /*Fixed cost of opening presorting facitlity at CZ k*/
param d1{k in K}; /*Distance etween CZ k and IRC (km)*/
param d2{k in K}; /*Distance between CZ k and recycling centre (km) */
param d, default 150; /*Distance between IRC and recycling centre (km)*/
param c1{m in M, k in K}, default 0.25;/*unit transportation cost of product m from CZ k to IRC ($/km-kg) */
param c1R{m in M, k in K}, default 0.25;/*unit transportation cost of refurbished product m from IRC to CZ k($/km-kg) */
param c2{m in M, k in K}, default 0.2;/*unit transportation cost of scrapped product m from CZ k to recycling ($/km-kg) */
param c3{m in M}, default 0.2;/*unit transportation cost of scrapped product m from IRC to recycling ($/km-kg) */
param RL{m in M}, default 10;/*unit cost of recycling/landfilling product m */
param I{m in M};/*Inspection cost per unit of product m at IRC */
param R{m in M};/*Refurbishing cost per unit of product m at IRC*/
param P{m in M, k in K}, default 10;/* Presorting cost per unit of product m at CZ k*/
param q{m in M,k in K, o in O}, default 0.5; /*fraction of  product m collected at CZ k which is good quality */
param Z{m in M,k in K};/*quantity of product m collected  at CZ k*/
param Ec{m in M}, default 0.03;/*CO2 Emissions for collecting products at CZ (kg/unit)*/
param Ep{m in M}, default 0.07;/*CO2 Emissions for presorting products at CZ (kg/unit)*/
param Ei{m in M}, default 0.09;/*CO2 Emissions for inspecting products at IRC (kg/unit)*/
param Eref{m in M}, default 0.21;/* Net CO2  Emissions for refurbishing products at IRC (kg/unit)*/
param Erec{m in M}, default 0.07;/*Net CO2 Emissions for recycling products (kg/unit)*/
param E, default 0.0001398;/*CO2 Emissions for transportation (kg of co2/kg transported-km)*/
param X{m in M};/*product weight in kg*/
param CE, default 0.018;/*Carbon emission cost/ Carbon tax in $/kg of CO2*/
param beta, default 0.05;/*inefficiency at presort */
param price{m in M, k in K};/*Selling price of refurbished product*/
param F{s in S}; /*Fixed cost of opening IRC */
param C{s in S}; /*Inspection capacity of IRC*/
param CC, default 16000;/* Carbon cap in kg of CO2*/
param Cp, default 0.27; /*Penalty for exceeding carbon cap in $*/
param Cc, default 0.135; /*Credit for not exceeding carbon cap in $*/
param Pr{o in O}; /*Probability values*/
```

```
param pi, default 30;/*Penalty for exceeding inspection  capacity of IRC */

#Model Variables
var fmkR{m in M, k in K, o in O}, >= 0;/*Quantity of refurbished product m sent from the IRC to CZ k*/
var fmR{m in M , o in O},>=0; /*quantity of product m refurbished at IRC*/
var fmI{m in M , o in O},>=0; /*quantity of product m inspected at IRC*/
var G{m in M, k in K , o in O}, >=0; /* quantity of scrapped product m sent from CZ k to recycling when "Presort is absent"*/
var f2{m in M, k in K , o in O},>=0;/*quantity of scrapped product m sent from CZ k to recycling _ Presort open */
var f3{m in M , o in O},>=0;/*quantity of scrapped product m sent from IRC  to recycling */
var Y{k in K}, binary;/*Opening and closing of presort*/
var u{s in S}, binary;/*IRC size*/
var ET {o in O}, >=0; /*total carbon emissions from transportation*/
var ET1, >=0; /* Carbon emissions from transportation: CZ to IRC */
var ET2, >=0; /* Carbon emissions from transportation: IRC to CZ*/
var ET3, >=0; /*Carbon emissions from transportation: CZ to recycling (Presort active)*/
var ET4, >=0; /* Carbon emissions from transportation: CZ to recycling (Presort absent)*/
var ET5, >=0;/*Carbon emissions from transportation: IRC to recycling*/
var EP {o in O}; /*total carbon emissions from  processes*/
var deltaP {o in O},  >= 0;/*Emissions greater than carbon cap stored in this variable*/
var deltaN {o in O},  >= 0;/*Emissions lesser than carbon cap stored in this variable*/
var H{m in M, k in K,o in O},>=0;/*quantity of product presorted */
var U{m in M, k in K,o in O},>=0;/*Quantity of products sent from CZ  to IRC after Presort */
var V{m in M, k in K,o in O},>=0;/*Quantity of products sent from CZ  to IRC without Presort */
var omegaP{o in O} , >= 0;/*Quantity of products to be inspected is more than inspection capacity of IRC*/
var omegaN{o in O} , >= 0;/*Quantity of products to be inspected is less than inspection capacity of IRC*/

#Objective function
maximize Profit: sum {o in O, m in M, k in K}Pr[o]*price[m,k]*fmkR[m,k,o]
- sum{s in S}F[s]*u[s]
- sum {k in K}FP[k]*Y[k]
- sum {o in O,m in M, k in K}Pr[o]*d1[k]*c1[m,k]*X[m]*fmI[m,o]
- sum {o in O,m in M, k in K}Pr[o]*d1[k]*c1R[m,k]*X[m]*fmkR[m,k,o]
- sum {o in O,m in M, k in K}Pr[o]*d2[k]*c2[m,k]*X[m]*f2[m,k,o]
- sum {o in O,m in M, k in K}Pr[o]*d2[k]*c2[m,k]*X[m]*G[m,k,o]
- sum {o in O,m in M}Pr[o]*d*c3[m]*f3[m,o]*X[m]
- sum {o in O,m in M,k in K}Pr[o]*P[m,k]*H[m,k,o]
- sum {o in O,m in M}Pr[o]*I[m]*fmI[m,o]
- sum {o in O,m in M}Pr[o]*R[m]*fmR[m,o]
- sum {o in O,m in M, k in K}Pr[o]*f2[m,k,o]*RL[m]
- sum {o in O,m in M, k in K}Pr[o]*G[m,k,o]*RL[m]
- sum {o in O,m in M}Pr[o]*f3[m,o]*RL[m]
- (CE*sum {o in O}Pr[o]*(ET[o]+EP[o]))
- sum {o in O}Pr[o]*Cp*deltaP[o]
+ sum {o in O}Pr[o]*Cc*deltaN[o]
-sum {o in O}Pr[o]*pi*omegaP[o];

#Flow balance at CZ
s.t. Flow_balance_at_CZ{m in M, k in K, o in O}:Z[m,k] = G[m,k,o] + H[m,k,o] + V[m,k,o];

# ensures that the quantity of products presorted will be less than the quantity of products collected
s.t. definition_H{k in K,o in O}:sum{m in M}H[m,k,o]<=Y[k]*sum{m in M}Z[m,k];

#Quantity of products sent from CZ  to IRC after Presort
s.t. Products_sent_to_IRDC1{m in M, k in K, o in O}: U[m,k,o] = H[m,k,o]*(q[m,k,o]+ (1 - q[m,k,o])*beta);

#Quantity of products sent  from CZ to IRC  without presort
s.t. Products_sent_to_IRDC2{k in K, o in O}: sum{m in M}V[m,k,o] <= C[3]*(1 - Y[k]);

# Quantity of scrapped products sent from CZ to recycling after presorting
s.t. Products_sent_from_CZ_to_recycling{m in M, k in K,o in O}:(1 - beta)*(1 - q[m,k,o])*H[m,k,o] = f2[m,k,o];

#Flow balance at Presort facility
s.t. Flow_balance_at_Presort{m in M, k in K, o in O}:H[m,k,o] = f2[m,k,o] + U[m,k,o];

# Total quantity inspected
s.t. Quantity_inspected{m in M, o in O}:fmI[m,o] = sum{k in K}U[m,k,o] + sum{k in K}V[m,k,o];
```

```
#  Flow balance at IRC
s.t. Product_from_Inspection_to_refurbishment{m in M, o in O}: fmR[m,o] = fmI[m,o] - f3[m,o];

# Quantity of scrapped products sent from IRC to recycling
s.t. Products_sent_from_IRDC_to_recycling{m in M, o in O}: f3[m,o] = sum{k in K} (1-q[m,k,o])*V[m,k,o] + sum{k in K} (1-q[m,k,o])*beta*H[m,k,o];

# ensures that all products refurbished at IRC are delivered to CZ
s.t.Refurbished_product_balance{m in M, o in O}:fmR[m,o]=sum{k in K}fmkR[m,k,o];

# capacity of IRC
s.t. IRDC_Capacity{o in O}:sum{m in M}fmI[m,o] = sum{s in S}C[s]*u[s] + omegaP[o] - omegaN[o];

#ensures IRC is selected before any product flow can be received for inspection
s.t. IRDC_Capacity2{m in M, o in O}:fmI[m,o] <= 300000*sum{s in S}u[s];

# only one size IRC is opened
s.t. IRDC_size: sum{s in S} u[s]<=1;

#Total Carbon emissions from transportation
s.t. Emissions_from_Transportation {o in O}:ET[o] = (sum{k in K}d1[k]*(sum{m in M}U[m,k,o]*X[m]))*E
+(sum{k in K}d1[k]*(sum{m in M}V[m,k,o]*X[m]))*E
+(sum{k in K}d1[k]*(sum{m in M}fmkR[m,k,o]*X[m]))*E
+(sum{k in K}d2[k]*(sum{m in M}f2[m,k,o]*X[m]))*E
+(sum{k in K}d2[k]*(sum{m in M}G[m,k,o]*X[m]))*E
+(d*(sum{m in M}f3[m,o]*X[m]))*E;

#Total carbon emissions from processes
s.t. Emissions_from_Processes{o in O}:EP[o] = sum{m in M}Ec[m]*(sum{k in K}Z[m,k])
+sum{m in M}Ep[m]*(sum{k in K}H[m,k,o])
+sum{m in M}Ei[m]*fmI[m,o]
-sum{m in M}Eref[m]*fmR[m,o]
-sum{m in M}Erec[m]*(sum{k in K}f2[m,k,o])
-sum{m in M}Erec[m]*f3[m,o]
-sum{m in M}Erec[m]*(sum{k in K}G[m,k,o]);

# emission balance
s.t. Carbon_cap_constraint{o in O}:ET[o]+EP[o] = CC + deltaP[o] - deltaN[o];

solve;

display Profit,fmkR,fmR,fmI,f2,f3,u,Y,G, ET, EP, deltaP, deltaN,omegaP, omegaN;

data;

param product :=3;
param CZ :=3;
param Size :=3;
param Scenario :=3;

param Pr:=
1 1
2 0
3 0;

#param q{m in M,k in K, o in O}
param q:=
1 1 1 0.2
1 2 1 0.2
1 3 1 0.2
2 1 1 0.2
2 2 1 0.2
2 3 1 0.2
3 1 1 0.2
3 2 1 0.2
3 3 1 0.2
```

```
1 1 2 0.5
1 2 2 0.5
1 3 2 0.5
2 1 2 0.5
2 2 2 0.5
2 3 2 0.5
3 1 2 0.5
3 2 2 0.5
3 3 2 0.5
1 1 3 0.9
1 2 3 0.9
1 3 3 0.9
2 1 3 0.9
2 2 3 0.9
2 3 3 0.9
3 1 3 0.9
3 2 3 0.9
3 3 3 0.9;

/*IRDC fixed costs*/
param F:=
1 200000/*small*/
2 350000/*medium*/
3 500000;/*large*/

/*Inspection capacity of IRDC*/
param C:=
1 120000
2 220000
3 300000;

/*Selling price of refurbished product*/
param price :=
1 1 200
1 2 200
1 3 200
2 1 300
2 2 300
2 3 300
3 1 250
3 2 250
3 3 250;

/*Fixed cost of opening presorting facitlity at CZ k*/
param FP :=
1 150000
2 150000
3 150000;

/*Distance between CZ k and IRDC (km)*/
param d1 :=
1 100
2 150
3 200;

/*Distance between CZ k and recycling centre (km) */
param d2 :=
1 200
2 300
3 400;

/*Inspection cost per unit of product m at IRDC */
param I :=
1 15
2 18
3 20;
```

```
/*Refurbishing cost per unit of product m at IRDC*/
param R :=
1 20
2 25
3 30;

/*quantity of product m collected  at CZ k*/
param Z :=
1 1 40000
1 2 40000
1 3 40000
2 1 45000
2 2 45000
2 3 45000
3 1 40000
3 2 40000
3 3 40000;

/*product weight in kg*/
param X:=
1 0.5
2 0.8
3 1.1;

end;
```

The above deterministic model is used for futher experiments with parameter changes given below.

For Experiment 4.7.2, return quality scenarios to study effects of varying π on the structure of the CLSC network are given in Table 4.12. Values of π are given in Table 4.13.

For Experiment 4.7.3, return quality scenarios used to study impact of increasing C_p on the network profit are given in Table 4.14. Values of C_p are given in Table 4.15.