Doctoral Dissertation Defense

Multi-Criteria Decision Making Optimization For Reverse Supply Chains

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Outline

- ✓ Background and Motivation
- ✓ Research Questions
- ✓ Research Studies
  - Problem Statement
  - Methods
  - Results
  - Summary
- ✓ Conclusion

Background and Motivation

Circular Economy

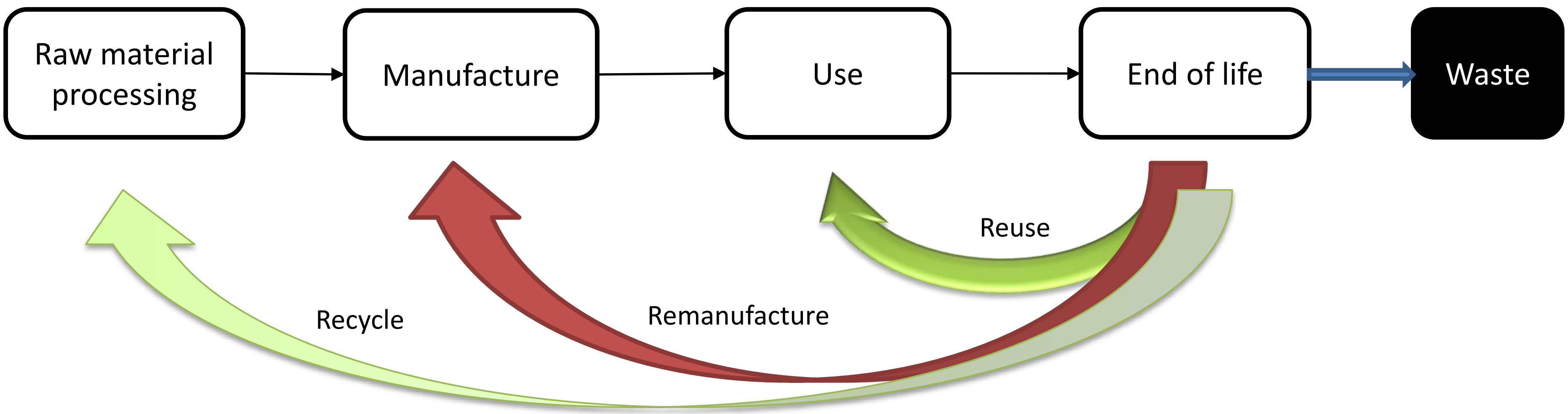


Figure 1. Generic Circular Economy

- The Circular Economy (CE) concept was developed as an alternative for the prevailing production paradigm of treating the environment as a waste reservoir, and was first raised forty years ago in a report to the European Commission (*Stahel & Reday-Mulvey, 1981*).

- It is described as turning end-of-life goods into resources for others and minimizing waste, applying concept of closing loops in industrial ecosystems.

Reverse Supply Chain

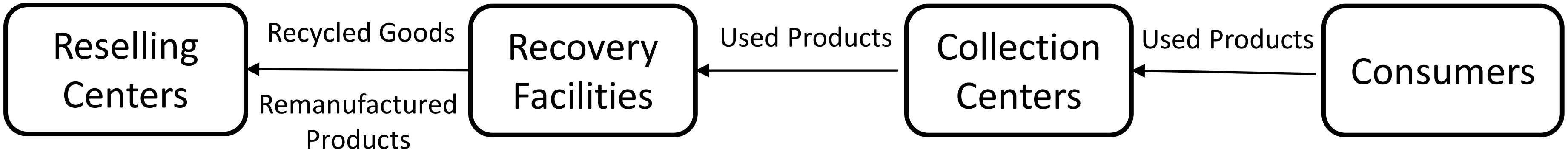


Figure 2. Generic reverse supply chain

In this work, a Reverse Supply Chain (RSC) is described as an initiative that plays an important role in the global supply chain for those who seek environmentally responsible solutions for their end-of-life (EOL) products. (*Gupta, 2013*)

Product Recovery (Recycling or Remanufacturing)

Recycling processes "retrieve the material content of used product without retaining the identity of their component". (*Pochampally et al., 2009*)

Remanufacturing is the process of transforming used, non-functional product or components to "like-new" conditions and recapturing value added to products during the manufacturing stage. (*Remanufacturing Industries Council, 2016*)

Some of the most commonly remanufactured product categories are:

- Aircraft components
- Automotive parts
- Electrical and electronic equipment
- Engines and components
- Medical equipment
- Office furniture
- Printing equipment
- Restaurant and food-service equipment

TOP FIVE INDUSTRIES IN THE U.S.
REMANUFACTURING 2011

	PRODUCTION	EMPLOYMENT
Aerospace	$13 billion	35,201
Heavy Duty/ Off-Road	$7.7 billion	20,870
Vehicle Parts	$6.2 billion	30,653
Machinery	$5.8 billion	26,843
IT Devices	$2.7 billion	15,442

Source: Reverse Logistics Magazine, Edition 74, 2015

Comparison of Environmental Benefits Between Recycling & Remanufacturing

Both methods reduce solid and hazardous wastes disposal

Remanufacturing outshines recycling in the reduction of energy use, greenhouse gasses, a contributing factor to global warming.

These differences can largely be attributed to the additional handling and transportation required for reintroducing recycled materials into the manufacturing process.

Remanufacturing Benefits:

- Conservation of materials.
- Reduced energy consumption during manufacturing.
- Reduced waste (and associated disposal costs).
- Lower price for comparable quality.

Source: Uma Reddy, Remanufacturing-The Ultimate Form of Recycling, 2016

Private Sector Examples in Remanufacturing

CATERPILLAR®

'Cat Reman', "35% of their costs lie in overheads while 65% lie in materials costs. The environmental benefits of their remanufacturing services are also extensive, 61% less greenhouse gases, a 93% reduction in water use, an 86% reduction in energy used, a reduction in waste sent to landfill of 99% and a 99% reduction in material use compared to making a new product."

http://www.caterpillar.com/en/company/brands/cat-reman.html

xerox

Xerox began remanufacturing operations in the early 1990s and is now a world leader in this field.

Through their comprehensive process of remanufacturing, globally, "Xerox has estimated to have saved $200m and recovered over 25,000 tonnes of materials from landfill.

Xerox. (2013). Environment, Health & Safety Report

Public Sector Examples in Remanufacturing

The USPS and Department of Interior both informed the Government Accountability Office (GAO) that they have reduced repair and maintenance **costs** by utilizing **remanufactured** vehicle components.
In addition to the cost savings, **remanufacturing** has **environmental benefits** as well.

USPS Fleet: **211,264** vehicles, one of the largest civilian fleets in the world.

Source: Government Accountability Office, 2015 report

The Federal Acquisition Regulation defines remanufactured parts as factory rebuilt to original specifications.

Source: Federal Acquisition Regulation §52.211-5

Remanufactured vehicle parts tend to be less expensive than comparable new parts. The principal remanufactured products in the motor vehicle sector are engines, transmissions, starter motors, alternators, steering racks, and clutches.

Source: U.S. International Trade Commission, 2012

Transition in Remanufacturing Sector

The US is the world's largest producer, consumer and exporter of remanufactured products.

A lack of awareness of remanufacturing and its benefits by dealers, customers and policymakers remains a major obstacle to growth of the industry.

Europe reports estimates that remanufacturing could grow to $100 billion, and up to 500,000 employees by 2030.

Source: European Remanufacturing Network, 2015

Source: U.S. International Trade Commission, 2012 report

European Remanufacturing Network

Optimization Phases in Supply Chains

Strategic planning involves long-term decisions that cannot be changed easily, (location and capacity of different facilities, transport links, and the type of product to be manufactured). Expensive to change and uncertainty market conditions.

Tactical planning includes all medium-term activities:

- Which markets will be supplied from which locations
- Planned buildup of inventories
- Subcontracting, backup locations
- Inventory policies
- Timing and size of market promotions

Operational level consists of day-to-day decisions:

- individual customer orders
- inventory control
- production planning to specific order, and delivery schedules over a short-term period

This level has less uncertainty in demand information.

Environmentally Conscious Manufacturing and Product Recovery (ECMPRO) Studies

Reference	Category/Scope
Fleischmann et al., 1997	Reverse logistics
Moyer & Gupta, 1997	Recycling/disassembly efforts in the electronics industry
Guide et al., 1999	Production planning and control for remanufacturing
Gungor & Gupta, 1999	Environmentally conscious manufacturing and product recovery
Ferguson & Browne, 2001	Product recovery and reverse logistics
Williams, 2006	Electronics remanufacturing processes
Chanintrakul et al., 2009	Environmentally conscious manufacturing and product recovery
Ilgin & Gupta, 2010	Reverse logistics network design
Ilgin & Gupta, 2012	Physical programming
Ilgin &Gupta, 2013	Reverse supply chains
Ilgin et al., 2015	Multi criteria decision making in ECMPRO
Curkovic & Sroufe, 2016	Environmentally responsible manufacturing
Matsumoto et al., 2016	Remanufacturing
Barange & Agarwal, 2016	Green supply chain management

Circular Economy and Reverse Supply Chains for Remanufacturing Studies

Reference	Category/Scope
Peters, 2016	Studies on Remanufactured Products Using Reverse Logistics
Derigent and Thomas, 2016	Circular Economy of Product and Material Recyclable
Govindan & Soleimani, 2016	Reverse Supply Chain Issues

Relevant Studies

Reference	Category
Pochampally et al., 2009	Strategic planning for reverse and closed-loop supply chains
Ferguson, 2009	Strategic issues in closed-loop supply chains with remanufacturing
Vadde et al., 2011	Pricing in multi-criteria for product recovery facilities
Das and Chowdhury, 2012	Designing reverse logistics network
Chaabane et al., 2012	Reducing emissions for RSC
Fahimnia et al., 2013	Carbon pricing on a closed-loop supply chain
Yang et al., 2014	Acquisition policy in remanufacturing
Gan et al., 2015	Pricing for new and remanufactured products
Rezaee et al., 2015	Green supply chain network design and carbon price
Bing et al., 2015	RSC design for household waste considering emissions

General Findings of The Literature

- Transportation cost plays an important role in RSC *(Pochampally et al., 2009; Ferguson, 2009; Das and Chowdhury, 2012;* Govindan & Soleimani, 2016*)*

- Labor cost has directly interfered with disassembly and assembly costs for remanufacturing *(Vadde et al., 2011; Yang et al., 2014; Gan et al., 2015)*

- Pricing carbon emissions, mainly affects transportation operations. *(Chaabane et al., 2012; Fahimnia et al., 2013; Rezaee et al., 2015)*

- The supply chain network configuration is sensitive to the carbon price *(Fahimnia et al., 2013; Bing et al., 2015; Peters, 2016; Govindan & Soleimani, 2016)*

- The cost benefits and environmental advantages of remanufacturing have made it an important strategy in many industries *(Hatcher et al., 2013; Kumar and Putnam, 2008; Lund, 1984; Webster and Mitra, 2007).*

Research Scope and Contribution

- This dissertation applies strategic and tactical level planning tools to help design a RSC with simultaneous consideration of economic, environmental, and social factors.

- The literature includes many forward supply chain developed studies and analysis, where the customer is the end of the process. However, the returns processes enabled by RSC covers many areas, including collecting, cleaning, disassembly, recovering, transportation, remanufacturing, reselling, and disposed or shredded products that cannot be reprocessed or are hazardous all over the reverse supply chain activities still need analytical development, as reviewed in the literature, more in chapter 2.

- The applied design approach is formulated as a multi-criteria optimization problem and explored using several available multi-criteria optimization techniques, more in chapter 4.

- Environmental concerns and changes in policy drive to redesign the RSC considering environmental policy, and for this addressing the gaps in RSC research by using a multi-criteria decision-making technique for the issues at the strategic and tactical levels of RSC with multiple stages to achieve effective and profitable operation.

Research Scope and Contribution

- This dissertation examines these issues with focus on strategic planning and tactical planning levels of RSC.

- The decision-making problems that are faced by strategic planners of reverse supply chains include first (1) collection center placement and capacity. Evaluation of the collection centers is the first stage in choosing the most profitable collection center. The evaluation of collection centers is a multi-criteria problem that may require the use of one of several tools available such as Goal Programming and Analytic Network Process.

- Next, (2) optimization of transport of EOL products while considering fuel and potential carbon costs, which has the focus of achieving transporting (used and remanufactured) products across a RSC while satisfying certain constraints that all fall under optimization of costs.

Research Scope and Contribution

- After that, the decision maker would be faced by tactical level of problem that includes (3) pricing of remanufactured products, which has not been given any importance in the past but the scale and unique processes of transforming used and recycled products into “like-new” conditions, and recapturing the missing values that added to the products during manufacturing stage, have made the pricing an important subject of research, and this problem determines a pricing policy for reusable and recyclable products in a multi-criteria environment when product recovery facilities (PRFs) passively accept discarded products and proactively acquire as needed where the goal is, to maximize the revenue and minimize the product recovery costs.

- The dissertation comprises **five** research papers that develop novel approaches and enhance the literature of RSC systems.

Research Questions

Research Questions

Using a multi-criteria decision-making approach, this dissertation considers the following research questions and develops general models for their study:

- Given fixed supply and demand, how many end-of-life products should be processed and to which candidate collection centers should they be transported? *(strategic planning: chapter 5)*

- What is an ideal pricing policy for remanufactured products? *(tactical planning: chapter 6)*

- What is the effect of a social cost of carbon (SCC) on the optimal configuration of RSC, and how does increasing the SCC affect the unit price of remanufactured equipment, relative to OEM? *(strategic planning: chapters 7-8)*

Research Studies

Study 1: A Linear Physical Programming Approach To Evaluating Collection Centers For End-of-life Products

Alkhayyal & Gupta 2015, NEDSI

- Physical linear programming (LPP) approach.
- Analytic Network Process (ANP).
- To determine the quantities of end-of-life products for transport from candidate collection centers to remanufacturing facilities while satisfying cost and capacity criteria.

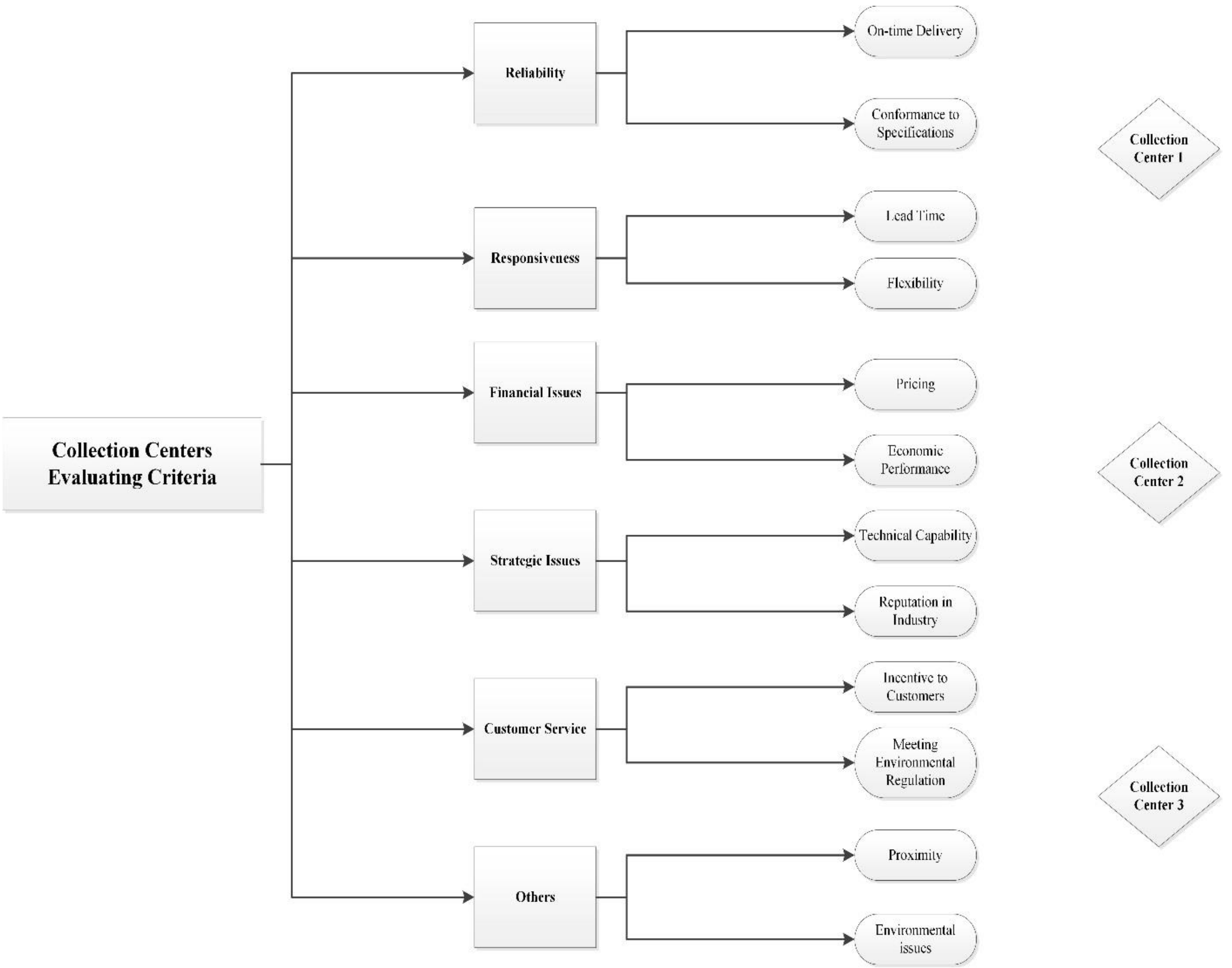
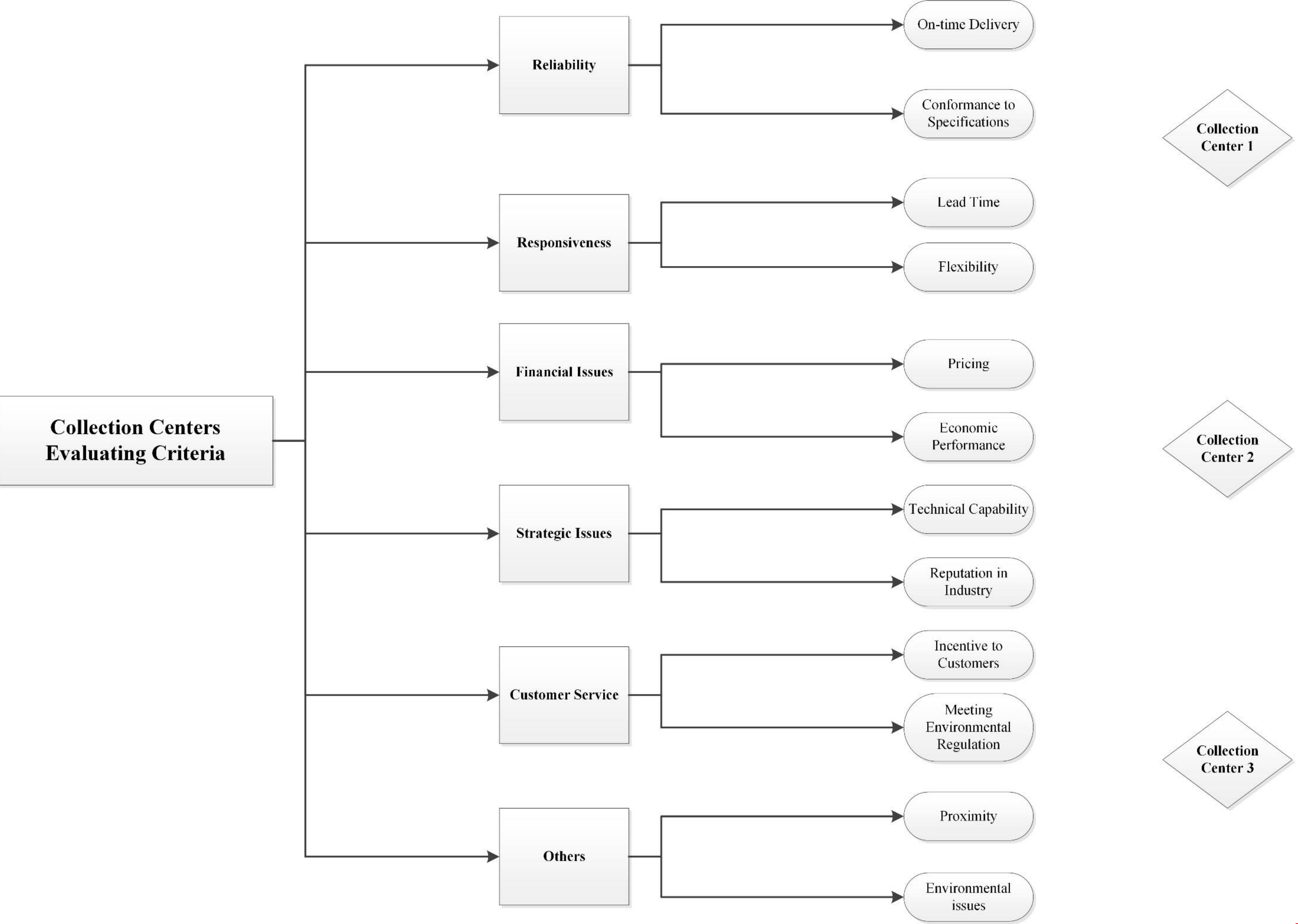


Figure 3. Hierarchical structure for ANP



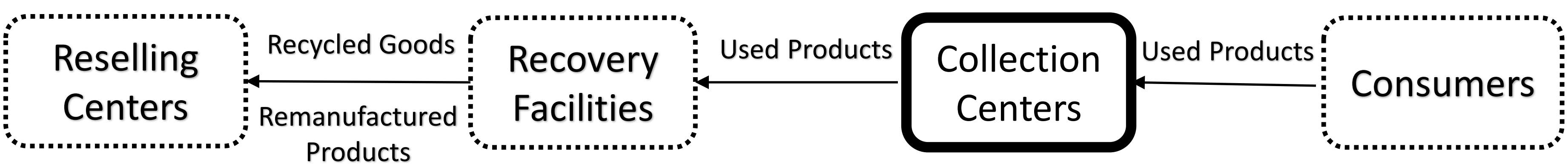
Collection Centers Evaluating Criteria
Reliability
On-time Delivery
Conformance to Specifications
Responsiveness
Lead Time
Flexibility
Financial Issues
Pricing
Economic Performance
Strategic Issues
Technical Capability
Reputation in Industry
Customer Service
Incentive to Customers
Meeting Environmental Regulation
Others
Proximity
Environmental issues
Collection Center 1
Collection Center 2
Collection Center 3

Problem Statement

- A scenario of evaluating collection centers based on efficiency is presented.
- The performance indices are determined by using ANP.
- These performance indices are used in developing an LPP model.

Optimization problems fit in one of two classifications:

- **Blind optimization** happens when we wish to minimize (or maximize) a function subject to constraints and we do not have any knowledge about the physical meaning of the objective function, constraints, or decision variable.
- **Physical optimization** takes place in the context of decision making that leads to the most satisfactory outcome (*Messac et al., 1996*)



Notation

c_i	Unit purchasing cost of used product at collection center i
cd_i	Disposal cost of used product i
t_i	Cost of transporting one used product from collection center i to remanufacturing facility j
d_j	Demand for used product j
i	Collection center index, $i = 1, 2, \ldots, s$
k_i	Capacity of collection center i
p_i	Probability of breakage of used products purchased from collection center i
p_{max}	Maximum allowable probability of breakage
Q_i	Decision variable representing the quantity to be purchased from collection center i
s	Number of candidate collection centers
w_i	Performance index of collection center i obtained by carrying out ANP

Problem Formulation

- The decision-making criteria in this model are presented in terms of ranges of different degree of desirability.

- Objective Functions:

  - Physical Programming Classes and Constraints
    - Soft Classes:
      - Class-1S: Smaller-Is-Better – Min:
      - *These are basically the cost criteria*
      - Class-2S: Larger-Is-Better – Max:
      - *These are basically the revenue criteria*

    - Hard Classes:
      - System Constraints

Soft Classes

- Class-1S: Smaller-Is-Better – Min:
  - Total Cost of Purchase (g1) given by
    - $g_1 = \sum_{ci \times Qi}$
  - Total Transportation Cost (g_2) given by
    - $g_2 = \sum_{ti \times Qi}$
  - Disposal Cost (g_3) given by
    - $g_3 = \sum_{(Qi \times pi) \times cdi}$

- Class-2S: Larger-Is-Better – Max:
  - Total Value of Purchase (g4) given by
    - $g_4 = \sum_{wi \times Qi}$

Hard Classes

- Hard Classes (System Constraints):
  - Class-1H Must be smaller, i.e., $g_p \leq t_{p,max}$
    - $Q_i \leq k_i$ (Capacity constraint)
  - Class-2H Must be larger, i.e., $g_p \geq t_{p,min}$
    - $d_i \times p_{max} \geq \sum_{Qi \times pi}$ (Quality constraint)
    - $Q_i \leq 0$ (Nonnegativity constraint)
  - Class-3H Must be equal, i.e., $g_p = t_{p,val}$
    - $\sum_{Qi = dj}$ (Demand constraint)

Numerical Example

Consider three candidate collection centers, Table 1 shows the data used for the LPP problem.

Table 1: Data for LPP model

Collection center	S1	S2	S3
Capacity	300	650	750
Unit purchasing cost	1.2	0.9	1.0
Breakage probability	0.03	0.015	0.01
Net demand for the product	1,000	1,000	1,000
Maximum acceptable breakage probability	0.025	0.025	0.025

The target values for each soft criterion are shown in Table 2:

The incremental weights obtained by LPP weight algorithm are shown in Table 3:

Table 2: Preference Table PP Model

Criteria	t_{p1}^{+}	t_{p2}^{+}	t_{p3}^{+}	t_{p4}^{+}
g_1	100	200	300	400
g_2	150	250	290	450
g_3	70	150	250	300
g_4	100	200	300	400

Table 3: Output of LPP Weight Algorithm

Criteria	$\Delta\omega_{p2}^{+}$	$\Delta\omega_{p3}^{+}$	$\Delta\omega_{p4}^{+}$
g_1	0.025	0.085	0.132
g_2	0.017	0.011	0.026
g_3	0.013	0.031	0.881
g_4	0.025	0.085	0.132

Results

Table 4 shows the results obtained by solving the problem using LINGO (v11).

Table 4: Results

Collection center	**ANP rating**	**Quantity ordered**
S1	0.2318	0
S2	0.2322	620
S3	0.5359	380

The total cost of purchase is found to be $938, and the total value of the purchase is 348

Study 1: Summary

- The LPP model was presented for identification of an efficient collection center in a region where an RSC was to be designed.
- Evaluation of the collection centers is the first stage in choosing the most profitable collection center.
- The results determined which candidate collection center should be chosen.

Research Questions

Using a multi-criteria decision-making approach, this dissertation considers the following research questions and develops general models for their study:

- Given fixed supply and demand, how many end-of-life products should be processed and to which candidate collection centers should they be transported? *(strategic planning level)*
- What is an ideal pricing policy for remanufactured products? *(tactical planning level)*
- What is the effect of a social cost of carbon (SCC) on the optimal configuration of RSC, and how does increasing the SCC affect the unit price of remanufactured equipment, relative to OEM? *(strategic planning level)*

Study 2: Optimal Pricing for Reusable and Recyclable Products Using Nonlinear Physical Programming

Alkhayyal & Gupta 2015, POMS

- In Japan, 200 million ink cartridges sold annually, remanufactured cartridges account for $15 million in sales, remanufactured ink cartridges sold at 20% to 30% less than new products (Matsumoto and Umeda, 2011).
- In the US, returned items have a value of nearly $100 billion annually (Guide et al, 2006)

Source: HP-Remanufactured Hardware

Motivation

- RSC systems enables a reverse flow of used products from consumers back to manufacturers, where they can be refurbished or remanufactured, to both economic and environmental benefit.

- Disassembly and remanufacturing processes have received little attention in industrial engineering and process cost modeling literature.

- The increasing scale of remanufacturing operations, worth nearly $50 billion annually in the United States alone, have made RSC pricing an important subject of research.

Background

- Consumers can find remanufactured products significantly more attractive, due to lower price for comparable quality (Abbey et al., 2015)
- The scale and unique processes of transforming used and recycled products into “like-new” conditions, and recapturing the missing values that added to the products during manufacturing stage, have made the pricing an important subject of research.

Source: Office Depot Brand (HP 60) Remanufactured Tricolor Ink Cartridge

Problem Statements

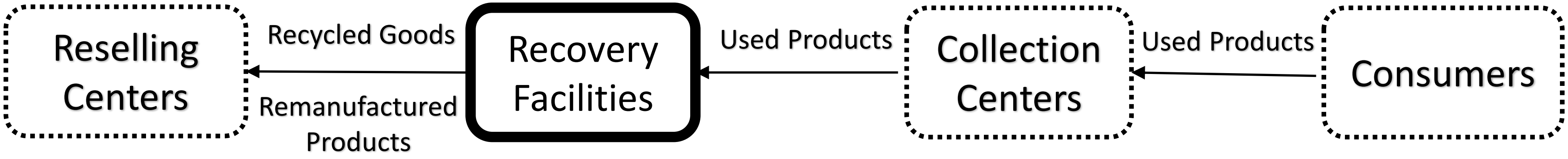
- What is an ideal pricing policy for remanufactured products?

http://www.officedepot.com/a/products/698559/Office-Depot-Brand-OD643WN-HP-60/

http://store.hp.com/us/en/pdp/hp-60-tri-color-original-ink-cartridge-p-cc643wn-140--1

Problem Statements

- Typically, there are two primary systems for obtaining used products from the end users:
  - The market-driven system: this relies on financial incentives to motivate end-users.
  - **The waste stream system**: this relies on diverting discarded products and passively accepts all product returns.
- Normally, there are four acquisition options to acquire a used product in practice:
  - Drop-off collection
  - Curbside collection
  - Point of Sale Collection
  - Mail-in Collection
- Product recovery facilities (PRFs) passively accept discarded products and proactively acquire as needed.



Pricing Challenges

- Competition between original equipment manufacturers (OEMs) and other PRFs.
- Requirement of costly, skilled workers for product recovery operations.
- Valuation of environmental considerations for inclusion into economic optimization tools.
- Uncertainty of the arrival time and the quantity for the discarded products.
- Inventory levels of recovered components.
- Promotional, markdowns, sales, and clearance price discounts to clear inventory.

Method

- Most of the pricing policies are non-linear problems, due to the environment they operate on.

- If you constrain your boundary to a smaller range, they can become linear. However, all linear smaller problems combined, due to the consideration of environmental effect, make it non-linear.

- A non-linear physical programming model for optimization of a pricing policy for remanufactured products that maximizes total profit and minimizes product recovery costs, was examined and solved.

Notation

R_T Total revenue.

C_D Total disposal cost.

C_P Total preparation cost.

C_H Total holding cost.

C_A Total disassembly cost.

C_Q Total acquisition cost.

C_S Total sorting cost.

P_N Net profit.

n_r Number of unique reusable components in a discarded product.

n'_r Number of unique recyclable components in a discarded product.

n_d Number of unique disposable components in a discarded product.

m_{ri} Multiplicity of reusable component i.

n'_{ri} Multiplicity of recyclable component i.

m_{di} Multiplicity of disposable component i.

w_{ri} Weight of reusable component i.

w'_{ri} Weight of recyclable component i.

w_{di} Weight of disposable component i.

w_p Weight of discarded product.

p_{ri} Selling price of remanufactured component i ($/unit).

p'_{ri} Selling price of high quality recyclable component i ($/lb).

p_{ai} Selling price of high grade as-is reusable component i ($/unit).

p_{si} Price of scrap grade reusable component i ($/lb).

p'_{si} Price of scrap quality recyclable component i ($/lb).

p_p Price of discarded product ($/lb).

λ_{ri} Demand for remanufactured component i.

λ'_{ri} Demand for high quality recyclable component i.

λ_{ai} Demand for high grade as-is reusable component i.

λ_{si} Demand for scrap grade reusable component i.

λ'_{si} Demand for scrap quality recyclable component i.

λ_p Demand for damaged discarded products.

β Yield of sorting process.

γ_{ri} Yield of high grade reusable component i.

γ'_{ri} Yield of high quality recyclable component i.

θ_{ri} Yield of remanufacturable quality reusable component i.

R_q Quantity of proactively acquired returns.

R_p Quantity of passively accepted returns.

C_s Cost to sort a discarded product.

C_r Cost to disassemble a product.

C_q Cost to acquire a discarded product (acquisition price) ($/unit).

C_{pi} Cost to remanufacture high grade reusable component i.

Problem Formulation

Categorize the Reusable and Recyclable Components:

1. High grade reusable components:
    a. First grade which have more economic value.
    b. Second grade which sold in as-is condition.
2. Scrap grade reusable components.
3. High quality recyclable components.
4. Scrap quality recyclable components.

To obtain an effective economic model the PRF prefers to sell the remanufactured components by the order of:

1. High grade as-is reusable.
2. High quality recyclable.
3. Scrap grade reusable.
4. Scrap quality recyclable.

Objective Functions-Physical Programming Classes and Constraints

- Soft Classes:
  - Class-1S: Smaller-Is-Better – Min:
    - Total Disposal Costs (g1) given by
      - g1 of product *i* is calculated by multiplying the component disposal cost by the number of component units disposed times the penalty cost to dispose the component.
        - $g1 = \sum_{i=1}^{nr} \mathrm{Cdi} + \sum_{i=1}^{n'r} \mathrm{d'di} + \sum_{i=1}^{nd} cddi$
    - Total Preparation Costs (g2) given by
      - g2 of product *i* is the summation of the cost of: remanufacture high grade reusable component *i* + prepare high quality recyclable component *i* + prepare high grade reusable component *i* for as-is sale.
        - $g2 = \sum_{i=1}^{nr} \mathrm{Cpi} + \sum_{i=1}^{n'r} \mathrm{C'pi} + \sum_{i=1}^{nd} Cxi$
    - Total Holding Costs (g3) given by
      - g3 of product *i* is the summation of both holding cost for high grade reusable component and high quality recyclable component.
        - $g3 = \sum_{i=1}^{nr} \mathrm{Chi} + \sum_{i=1}^{n'r} \mathrm{C'hi}$

Objective Functions-Physical Programming Classes and Constraints

- Soft Classes:
  - Class-1S: Smaller-Is-Better – Min:
    - Total Disassembly Costs (g4) given by
      - g4 of product *i* is calculated by multiplying the cost to disassemble a product by the sum of quantity of proactively acquired returns and the quantity of passively accepted returns.
        - $g4 = \mathrm{Cr}(\beta\mathrm{Rp} + \mathrm{Rq})$
    - Total Acquisition Costs (g5) given by
      - g5 of product *i* is calculated by multiplying the cost to acquire a discarded product by the quantity of proactively acquired returns.
        - $g5 = \mathrm{CqRq}$
    - Total Sorting Costs (g6) given by
      - g6 of product *i* is calculated by multiplying the cost to sort a discarded product by the quantity of passively accepted returns.
        - $g6 = \mathrm{CsRp}$

Objective Functions-Physical Programming Classes and Constraints

- Soft Classes:
  - Class-2S: Larger-Is-Better – Max:
    - Total Revenue (g7) given by
      - g7 is the summation of: the selling price of remanufactured component *i* ($/unit) + selling price of high quality recyclable component *i* ($/lb) + selling price of high grade as-is reusable component *i* ($/unit) + price of scrap grade reusable component *i* ($/lb), price of scrap quality recyclable component *i* ($/lb) + the price of discarded product ($/lb).

$$g7 = \sum_{i=1}^{nr} \mathrm{Pri\ Qri} + \sum_{i=1}^{n'r} \mathrm{P'ri\ Q'ri} + \sum_{i=1}^{nr} Pxi\ Ari + \sum_{i=1}^{nr} Psi\ Fri + \sum_{i=1}^{n'r} P'si\ F'ri + PpJ$$

Objective Functions-Physical Programming Classes and Constraints

- Hard Classes:
  - Class-1H Must be smaller, i.e., $g_p \le t_{p,max}$:
    1. Demand for remanufactured component *i*.
    2. Demand for high quality recyclable component *i*.
    3. Demand for high grade as-is reusable component *i*.
    4. Demand for scrap grade reusable component *i*.
    5. Demand for scrap quality recyclable component *i*.
    6. Demand for damaged discarded products.

  - Class-2H Must be larger, i.e., $g_p \ge t_{p,min}$:
    - It has one constrain, which is, all the demands for discarded products are positive.

Non-linear Physical Programming Model

- MINIMIZE $J = \log_{10} \{1/n_{sc}\ \Sigma\ zi\ [\mu i\ (x)]\}$ (for soft classes)

  Subject to

  $\mu_i\ (x) \leq \boldsymbol{t}^{+i5}{}_{+}$ (for class 1S objectives)

  $\mu_i\ (x) \geq \boldsymbol{t}\ ^{-}{}_{i5\ -}$ (for class 2S objective)

  $\mu_j\ (x) \leq \boldsymbol{t}_{i,\ max}$ (for class 1H objectives)

  $\mu_j\ (x) \geq \boldsymbol{t}_{i,\ min}$ (for class 2H objectives)

  $\boldsymbol{x}_{j,\ min} \leq x_j \leq \boldsymbol{x}_{i,\ min}$ (for design variables)

where $t_{i,\ max},\ t_{i,\ min,\ and}\ t_{i,\ val\ =}$ specified preferences values for the *i*th hard objective; $t_{i,\ min}\ \&t_{i,\ max}$ = minimum and maximum values, respectively, for $x_{j;}$ ranges of desirability, $t^{+}{}_{i5}$ and $t^{-}{}_{i5,}$ are provided by the designer; and n_{SC} = number of soft objectives. In the above formulation, hard classes are treated as constraints and soft classes are part of the objective function (Messac, 2006).

Numerical Example

- Consider that a PRF is processing discarded PCs according to configuration and data costs shown in Table 5 and Table 6.

Table 5: Product configuration

Index (i)	**Component**	**Multiplicity**	**Weight**	**Yield**	**Yield**	**Disposal**
(Recycle)						**Limit (lb)**
1	14" FHD	1	1.10	0.85	n/a	26
2	Chassis	1	0.68	0.95	n/a	38
3	128MB RAM	1	0.05	0.70	n/a	25
4	64MB RAM	1	0.02	0.80	n/a	20
5	1.44MB FD	1	0.68	0.75	n/a	19
(Reuse)						
1	24x CD-ROM	1	0.90	0.90	0.50	50
2	10GB HD	2	1.30	0.70	0.60	90
(Dispose)						
1	2.80 GHz Processor	1	0.40	n/a	n/a	120

Numerical Example

Table 6: Cost data

Preparation *Cost*	**As-Is** Cost	**Holding** Cost	**Disposal** Cost	**Disposal** Penalty
(Recycle)				
7	n/a	1.02	8	9
9	n/a	1.01	9	6
8	n/a	0.95	7	4
9	n/a	1.03	7	6
8	n/a	1.04	7	7
(Reuse)				
12	3	1.05	6	8
8	5	1.04	9	6
(Dispose)				
n/a	n/a	n/a	10	14

The weights were obtained by using Matlab Code for a PP algorithm (Messac, 2015), based on the DM preference ranges for μ in Table 7:

Table 7: Preference ranges for μ

Highly Desirable	**< 89**
Desirable	89-70
Tolerable	70-51
Undesirable	51-30
Highly undesirable	30-19
Unacceptable	> 19

Results

Table 8 shows the results obtained by solving the problem.

Table 8: Results

	Price			Inventory		
Component	**High grade/ quality($/lb)**	**Scrap grade/ Quality($/lb)**	**As-Is ($)**	**High grade/ quality(lb)**	**As-Is (units)**	**Disposed (lb)**
14" FHD	9.52	6.15	n/a	2.10	n/a	0.96
Chassis	31.52	6.23	n/a	0.70	n/a	0.57
128MB RAM	24.08	5.94	n/a	0.32	n/a	0.62
64MB RAM	12.57	3.02	n/a	0.73	n/a	0.30
1.44MB FD	24.81	4.07	n/a	0.21	n/a	3.72
24x CD-ROM	90.42	3.13	n/a	0.42	0	0.14
10GB HD	40.03	0.76	21.36	2.71	2.10	14.50
2.80GHz Processor	n/a	n/a	14.09	n/a	n/a	17.04
Computer	n/a	4.02	n/a	n/a	n/a	0.30

The overall profit is $1187.89; price to purchase a PC (g5) = $4.10, quantity of returns to purchase (Rq) = 29 units.

Study 2: Summary

- This is tactical planning level study that determines optimizing the pricing policy of reusable and recyclable products.
  - To maximize the total profit,
  - Minimize the product recovery costs, which includes:
    - disposal cost,
    - preparation cost,
    - holding cost,
    - disassembly cost,
    - acquisition cost,
    - and sorting cost.

- The pricing of returned products was an issue, since the competition between OEMs and other PRFs, uncertainty of arrival and demand, and sales were the challenges that are faced by PRFs.

Research Questions

Using a multi-criteria decision-making approach, this dissertation considers the following research questions and develops general models for their study:

- Given fixed supply and demand, how many end-of-life products should be processed and to which candidate collection centers should they be transported? *(strategic planning level)*
- What is an ideal pricing policy for remanufactured products? *(tactical planning level)*
- What is the effect of a social cost of carbon (SCC) on the optimal configuration of RSC, and how does increasing the SCC affect the unit price of remanufactured equipment, relative to OEM? *(strategic planning level)*

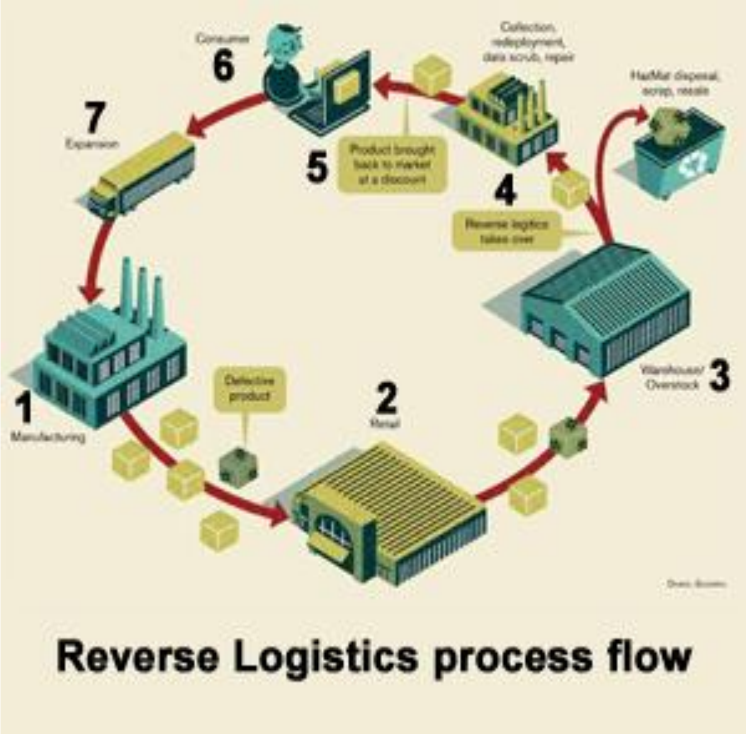
Study 3: Reverse Supply Chain Network Design and Optimization Considering Carbon Cost

Alkhayyal, Gupta, & Eckelman 2016, Journal of Cleaner Production (in Preparation)

There are major efforts underway to create a circular economy to reduce non-renewable resource use and waste.

One important aspect of these efforts is the development of RSC systems.

What is the effect of a social cost of carbon (SCC) on the optimal configuration of RSC, and how does increasing the SCC affect the unit price of remanufactured equipment, relative to OEM?



Source: Patrick Burnson, Supply Chain 24/7, 2010

Reselling Centers ← (Recycled Goods / Remanufactured Products) ← Recovery Facilities ← (Used Products) ← Collection Centers ← (Used Products) ← Consumers

Background

Research on Greenhouse Gas Emissions in RSC:

- **Schipper (2006)**: The U.S. Energy Information Administration reports that manufacturing activities are accountable for 84% of energy-related industry CO_2 emissions and 90% of industry energy consumption.

- **Chaabane et al., (2012)**: Reducing emissions generated by a supply chain has become an important goal. The “trade-offs in the supply chain are no longer just about cost, service and quality, but also about cost, service, quality and carbon”.

- **Biswas et al., (2013)**: compared the environmental impacts among repaired, remanufactured, and new air compressors.
  - The results showed that a remanufactured air compressor led to a 96% reduction in GHG emissions compared to the alternatives.

Background

Research on Greenhouse Gas Emissions in RSC:

- **Fahimnia et al., (2013):** evaluated the forward and RSC on carbon footprint, with GHG emissions evaluated in terms of carbon cost dollar.

- **Wang et al., (2016)**: studied the impact carbon emissions constraints on production decisions in four mathematical models.
  - Found that the manufacturer needs more capital to achieve the maximum profit when the carbon emission constraint is considered.

- **Fatimah & Biswas (2016)**: Concerning carbon-constrained economy matters, replacing the original manufactured product with a remanufactured product generates large revenue in terms of carbon-saving returns.

Background

Input-Output Life Cycle Assessment (EIO-LCA) Studies of Remanufacturing:

- **Mihelcic et al., (2003)**: studied the life cycle stages of products. In most cases, reusing and remanufacturing were preferred since they required fewer natural resources, less energy and time, and lower costs.

- **Zhou et al., (2006)**: EIO-LCA was used to study statistical data on U.S. cellular phone shipments and average bills of material from 2003 and 2004 with respect to the environmental impact of upstream cellular phone production chains, such as, air pollutants, energy use, and greenhouse emissions.
    - They concluded that reusing, recycling, refurbishing, and remanufacturing cellular phones and their components were better alternatives for environmental risk reduction.

Background

Input-Output Life Cycle Assessment (EIO-LCA) Studies of Remanufacturing:

- **Latham (2016)**: EIO-LCA was used to study the economic and environmental impact of manufactured traditional vehicles and remanufactured new vehicles.
  - The results showed that in every EIO-LCA category remanufactured vehicles were a better alternative than manufactured vehicles both economically and environmentally.

Japan Example

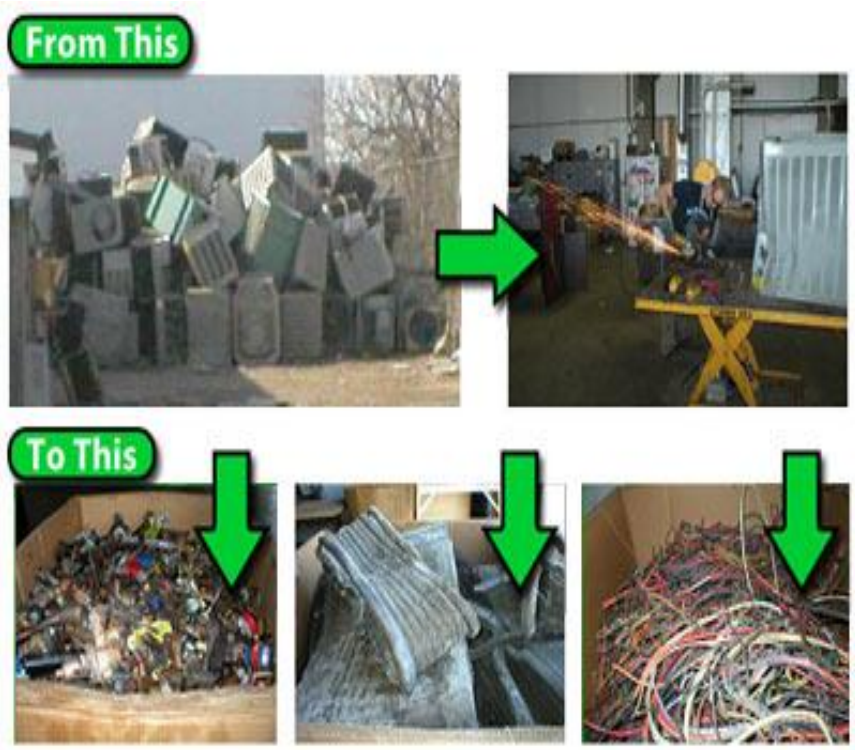
- **Daikin (2015):** In Japan, at least 80% of air conditioner materials are recycled under the home appliance recycling law. In 2014 alone, Japan recovered about 230,000 products, totaling 10,783 tons, with an 89% recycling ratio.

A worker dismantles air conditioners in preparation for recycling at the Panasonic Eco Technology Center (PETEC) on July 2, 2009 in Kato, Hyogo, Japan. Source: Junko Kimura/Getty Images AsiaPac (2009)

Adapted from: Tyrone Turner (2013)

Recker & Boerger (Ohio) Example

- Air Conditioners are collected over the summer and taken apart throughout the winter, recycling every component.
- Even the oil from the compressor is collected for reuse.



Photos taken by Recker & Boerger HVAC, Ohio

Methods

A deterministic equilibrium model was used to determine the effects of internalizing a cost of RSC greenhouse gas (GHG) emissions into optimization models.

Changes in optimal facility use, transportation logistics, and pricing/profit margins were all investigated against a variable cost of carbon, using case study system created based on actual data from sites in the Boston area.

A comprehensive study for quantitative evaluation and performance of the model has been done using Orthogonal Arrays.

PARIS2015
UN CLIMATE CHANGE CONFERENCE
COP21·CMP11

21st Conference of the Parties UNFCCC

Methods

A case study investigated based on actual sites in the Boston area to compare the economic and environmental impacts on remanufactured air conditioners in a RSC model, and to test the influence of GHG emissions pricing on different configurations of a RSC.

The air conditioners have large and growing market and are a target of remanufacturing efforts due to the presence of refrigerants with mandated handling rules.

U.S. Environmental Protection Agency

Methods

Independent Statistics & Analysis
U.S. Energy Information Administration

Commercial Buildings Energy Consumption Survey (CBECS) and Manufacturing Energy Consumption Survey (MECS) databases, based on the New England census division.

A deterministic model with minimum shipments is developed.

A deterministic model with relaxation constraints is developed to examine the effect of carbon price uncertainty on supply chain network decisions, that consideres13 scenario groups for carbon pricing with identical demand scenarios.

eiolca.net

http://www.eiolca.net/index.html

The EIO-LCA sector chosen was, the U.S. 2002 Benchmark for air conditioning, refrigeration, and warm air heating equipment manufacturing

Methods

Mixed-integer linear programming (MILP) is a special case, in which 0–1 integer linear programming involves integers and non-integers for both constrained variables.

Design of Experiments Study:

- Taguchi Orthogonal Array (OA)
  - A full-factorial design with 13 factors requires an extensive number of experiments (that is, 1.59E+4)
  - L_{27} OA was chosen, which requires 27 experiments while satisfying 13 factors, each with three different levels.
- Regression analysis

Methods: Design of Experiments Study

Table 9: Factors and factor levels used in design-of-experiments study

No	Factor	Unit	Levels		
			1	2	3
1	Transportation Cost	$	0.5	1	1.5
2	Energy Cost - fix	$/kWh	0.07	0.12	0.27
3	Energy Cost - variable	$/kWh	0.07	0.13	0.27
4	Rent Cost	$	2.69	5.39	8.08
5	Labor Cost	$	8.26	16.52	24.78
6	Social Cost of Carbon	$/kg	0.00	40.00	120.00
7	Shortage Cost	$	50.00	90.00	130.00
8	Remanufacturing Cost	$	8.26	16.52	24.78
9	Mean demand rate	Parts	229	458	687
10	Retrieval Cost	$	10.8	21.6	32.4
11	Inventory Cost	$	2	4	6
12	Inventory level	Parts	1250	2500	3750
13	Supply rate	Parts	1049	2098	3147

Methods: Taguchi Orthogonal Array Design

Table10: L27 OA with 27 experiments

Experiments	Factors												
	Transportation	Energy - fix	Energy - variable	Rent	Labor	Social Cost of Carbon	Shortage	Remanufacturing	Mean demand rate	Retrieval	Inventory	Inventory Level	Supply
1	1	1	1	1	1	1	1	1	1	1	1	1	1
2	1	1	1	1	2	2	2	2	2	2	2	2	2
3	1	1	1	1	3	3	3	3	3	3	3	3	3
4	1	2	2	2	1	1	1	2	2	2	3	3	3
5	1	2	2	2	2	2	2	3	3	3	1	1	1
6	1	2	2	2	3	3	3	1	1	1	2	2	2
7	1	3	3	3	1	1	1	3	3	3	2	2	2
:	:												
:	:												
25	3	3	2	1	1	3	2	3	2	1	2	1	3
26	3	3	2	1	2	1	3	1	3	2	3	2	1
27	3	3	2	1	3	2	1	2	1	3	1	3	2

1: Low Level. 2: Medium Level. 3: High Level

Notations:

Variables	Definition
$O1$	Occupied space by remanufacturing unit;
$O2$	Occupied space by used-product unit;
$RCAP_v$	Remanufacturing facility *v* capacity;
R_{ut}	Retrieval cost per unit at collection center *u*;
SH_u	Shortage cost per unit at collection center *u*;
H_u	Holding cost per unit at collection center *u*;
D_w	Demand of products at reselling center *w*;
X_{uv}	Decision variable for the number of units transferring from collection center u to remanufacturing facility *v*;
Y_{vw}	Decision variable for the number of units transferring from remanufacturing facility v to reselling center *w*;
P_v	Reprocessing cost per unit at remanufacturing facility *v*;
C_u	Storage capacity at collection center *u* per unit;
C_{1v}	Storage capacity at remanufacturing facility v per remanufactured unit;
C_{2v}	Storage capacity at remanufacturing facility v per used unit;
C_w	Storage capacity at reselling center *w* per unit;
SUP_u	Supply at collection center *u*;
TX_{uv}	Transportation cost from collection center *u* to remanufacturing facility *v*, per unit;
TZ_{vw}	Transportation cost from remanufacturing facility *v* to reselling facility *w*, per unit;
CX_{uv}	GHG emissions cause by transferring from collection center *u* to remanufacturing facility *v*, in tons per mile;
CX_{vw}	GHG emissions cause by transferring from remanufacturing facility *v* to reselling center *w*, in tons per mile;
CY	GHG emissions factor of a remanufacturing facility *v*, in tons per ft3;
CZ	GHG emissions factor of a remanufacturing facility *v*, in tons per kWh of operation;
EX_u	Energy cost at collection center *u* per unit;
EY_w	Energy cost at remanufacturing facility *v* per unit;
EZ_w	Energy cost at reselling center *w* per unit;
RX_u	Rent cost at collection center *u* per unit;
RY_v	Rent cost at remanufacturing facility *v* per unit;
RZ_w	Rent cost at reselling center *w* per unit;
LX_u	Labor cost at collection center *u* per unit;
LY_v	Labor cost at remanufacturing facility *v* per unit;
LZ_w	Labor cost at reselling center *w* per unit;
u	Collection center;
v	Remanufacturing facility;
w	Reselling center;
Z_v	Binary variable (0/1) for selection of remanufacturing facility *v*.

Problem Formulation

Minimize

Retrieval cost $\sum_{u}\sum_{v} R_u X_{uv} +$

Transportation cost $\sum_{u}\sum_{v} TX_u X_{uv} + \sum_{v}\sum_{w} TY_u Y_{uv} +$

Remanufacturing cost $\sum_{v}\sum_{w} P_v Z_{vw} +$

Inventory cost $\sum_{u}\sum_{v} R_u * X_{uv} + \sum_{v}\sum_{w} Pu * Y_{uv} + \{(Dw - SUPu) * (Z)\} * Hu +$

Rent cost $\sum_{u} RXu + \sum_{v} RYv + \sum_{w} RZw$

Labor cost $\sum_{u} LXu + \sum_{v} LYv + \sum_{w} LZw$

Energy cost $\sum_{u} EXu + \sum_{v} EYv + \sum_{w} EZw$

Greenhouse Gas (GHG) Emissions $\sum_{u} CXuXw + \sum_{V} CYvYv + \sum_{w} CZwZw$

Shortage cost $\{(Dw - SUPu) * (1 - Z)\} * SHu$ (8-1)

Problem Formulation

Subject to

Demand constraint must be met while minimizing the total cost of production and inventory. (8-2)

$$\sum_{v} Yvw \geq D_w \; ; \; \forall \, w$$

Remanufacturing facility total output is at most its total input

$$\sum_{u} Xuv \geq \sum_{v} Yvw \; ; \; \forall \, v \qquad (8\text{-}3)$$

Remanufacturing items occupied space at each remanufacturing facility is at most its capacity, and total space occupied at each collection center by returned items at most its capacity

$$\sum_{w} O_1 * Yvw \leq C_{1v} * Yv; \forall v \qquad (8\text{-}4)$$

$$\sum_{u} O_2 * Yuv \leq C_{2v} * Yv; \forall v \qquad (8\text{-}5)$$

Total space occupied at each remanufacturing facility by returned items at most its capacity

$$\sum_{v} O_2 * Xuv \leq C_u; \forall u \qquad (8\text{-}6)$$

Total space occupied at reselling center by returned items at most its capacity

$$\sum_{v} O_1 * Yuv \leq C_w * Yw; \forall w \qquad (8\text{-}7)$$

Non-negativity constraint

$$X_{uv} \geq 0 \; ; \; \forall \, u, v \qquad (8\text{-}8)$$

$$Y_{uv} \geq 0 \; ; \; \forall \, w, v \qquad (8\text{-}9)$$

Case Study

It is based on actual sites in the metro area of Boston, Massachusetts, USA and considers three collection centers (located in Melrose, Canton, and Natick), two remanufacturing facilities (located in Taunton and Hingham), and three reselling centers (located in Revere, Boston, and Somerville).

The actual distances in miles between the locations were considered, fuel costs and GHG emissions, assuming the gasoline price per gallon is $2.14 as of October 2015.

The number of laborers, their annual salaries, and the size of the space were also considered. The study reflects a breakdown of the cost factors: rent, labor, energy, GHG emissions, and transportation, by facility type, on-site, inter-facility, and total tCO_2e from on-site electricity use by unit.

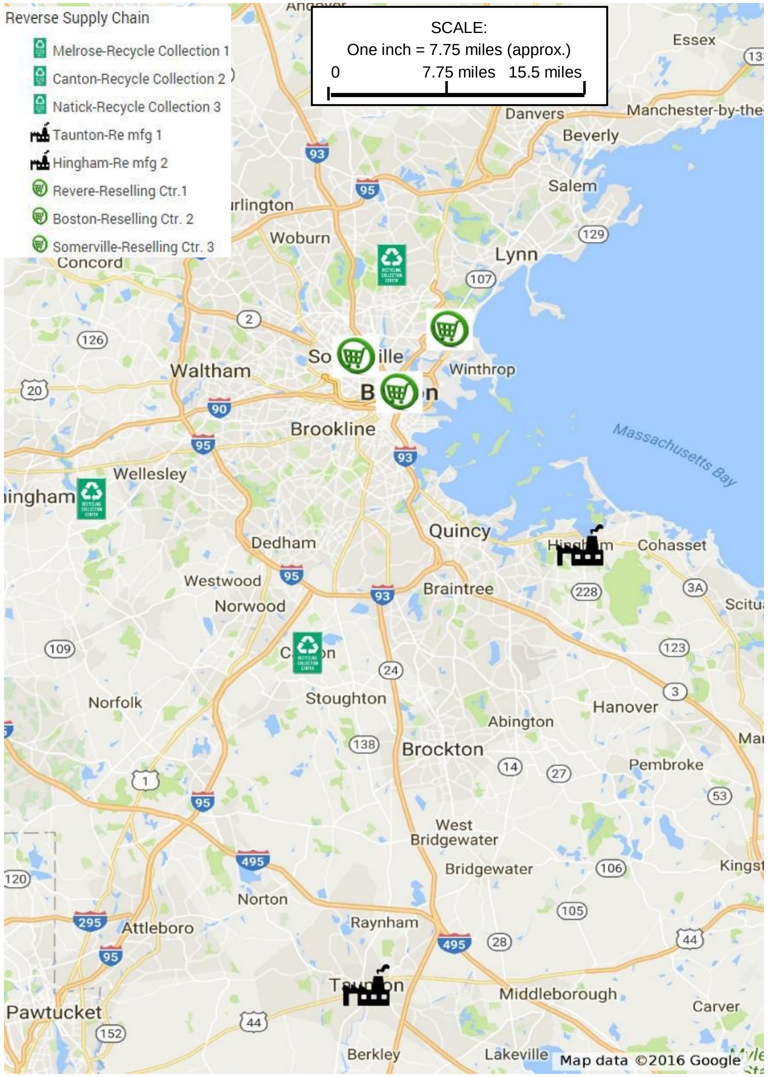


Figure 4: The actual sites in the Boston, Massachusetts area

Case Study

- CBECS was for collection centers and reselling centers energy data, and for this survey, New England region with retail (other than mall) building activity was chosen.
- Energy sources of electricity, natural gas, and fuel oil data were examined and their usage inside each building.

http://www.lg.com/lg-LW1213ER

- MECS was used for remanufacturing facilities energy data, and for this survey, New England region with appliances subsector was chosen.
- Energy sources of electricity, natural gas, distillate fuel oil and diesel, and residual fuel oil data were examined and their usage inside each facility.

It considers a mid-size LG A/C unit, model LW1213ER, and a market price of $349.99.

Case Study: Data

Table 11: Collection Centers Actual Data

Collection Center	AC unit received (year)	Pick up/drop off fee $ per item	Total items per year	Total income ($/year)
Canton	107	$20	509	$10,180
Natick	176	$25	837	$20,925
Melrose	175	$20	752	$15,040

Table 12: Rent Cost

Cities	Space (Sq ft)	Rent per Sq ft/year	Total rent per year
Canton	1000	$14.4	$4,220
Natick	3000	$10.5	$10,575
Melrose	1500	$15.0	$7,460
Taunton	10000	$11.0	$110,000
Hingham	9801	$8.0	$78,408
Revere	2700	$10.0	$27,000
Boston	5100	$25.0	$127,500
Somerville	4000	$17.0	$68,000

Case Study: Data

Table 13: Number of laborers and their cost per year

Cities	Number of laborers	Labor cost per year
Canton	5	$93,600
Natick	3	$56,160
Melrose	4	$74,880
Taunton	15	$280,800
Hingham	17	$318,240
Revere	4	$74,880
Boston	3	$56,160
Somerville	6	$112,320

Table 14: Trip distances between locations in miles

To From	Taunton	Hingham
Melrose	52.8	28.1
Canton	17.2	19.3
Natick	37.0	30.5
Revere	45.0	24.0
Boston	40.0	19.0
Somerville	43.0	22.0

Social Cost of Carbon

- Environmental Protection Agency (EPA) and other federal agencies use the social cost of carbon (SCC) to estimate the climate benefits of rulemakings.
- The SCC is an estimate of the economic damages associated with a small increase in carbon dioxide (CO_2) emissions, conventionally one metric ton, in a given year.
- This dollar figure also represents the value of damages avoided for a small emission reduction (i.e., the benefit of a CO_2 reduction). (EPA, Sep 29, 2016)

Source: Aurich Lawson / Thinkstock, 2015

Results: Deterministic Model with Minimum Shipments

In the absence of a carbon tax, the unit price was $212 with a profit margin estimated to be 26.4% for $288 selling price according to current refurbished market price (LG Model: LW1213ER Refurbished, 2015).

With $40/ton CO_2 equivalent (tCO_2e) tax reduced the profit margin to 19.1%

The total remanufacturing cost is $107,002 ($233 per unit), and the devolved model is $116.99 per unit less than the current market price of ($349.99)

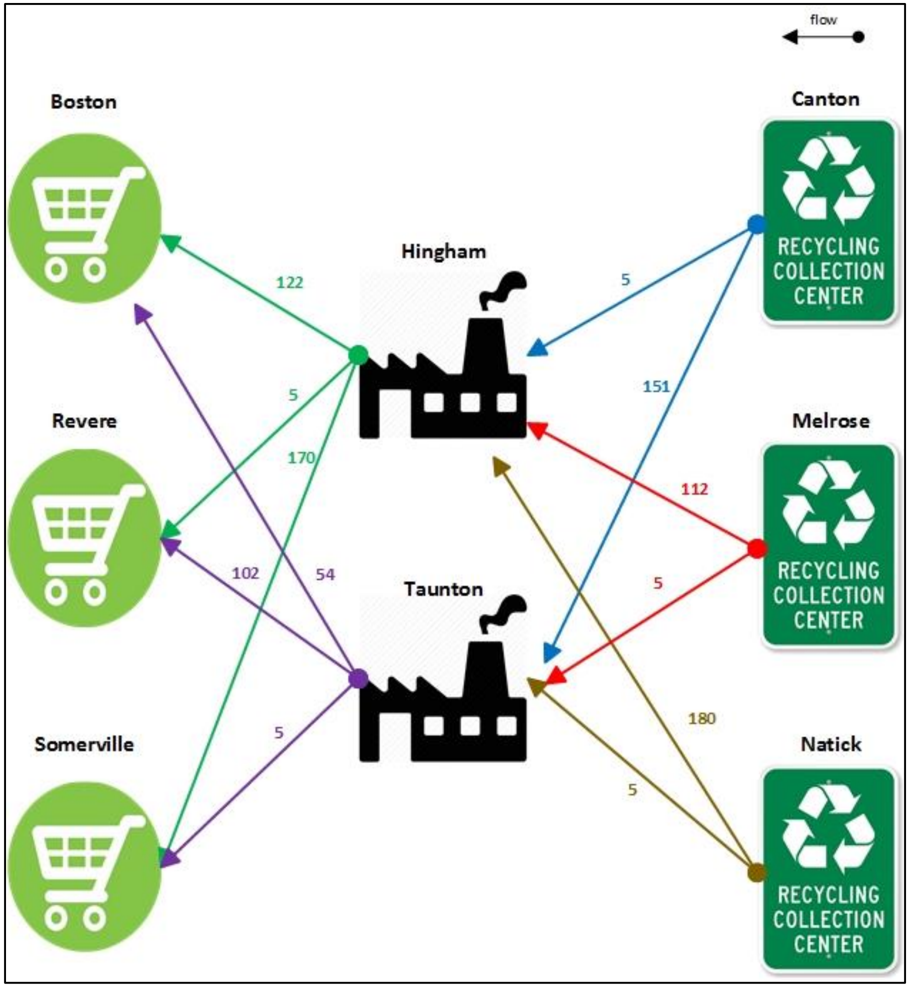


Figure 9: Optimal number of items transported within the RSC

Results: Deterministic Model with Minimum Shipments

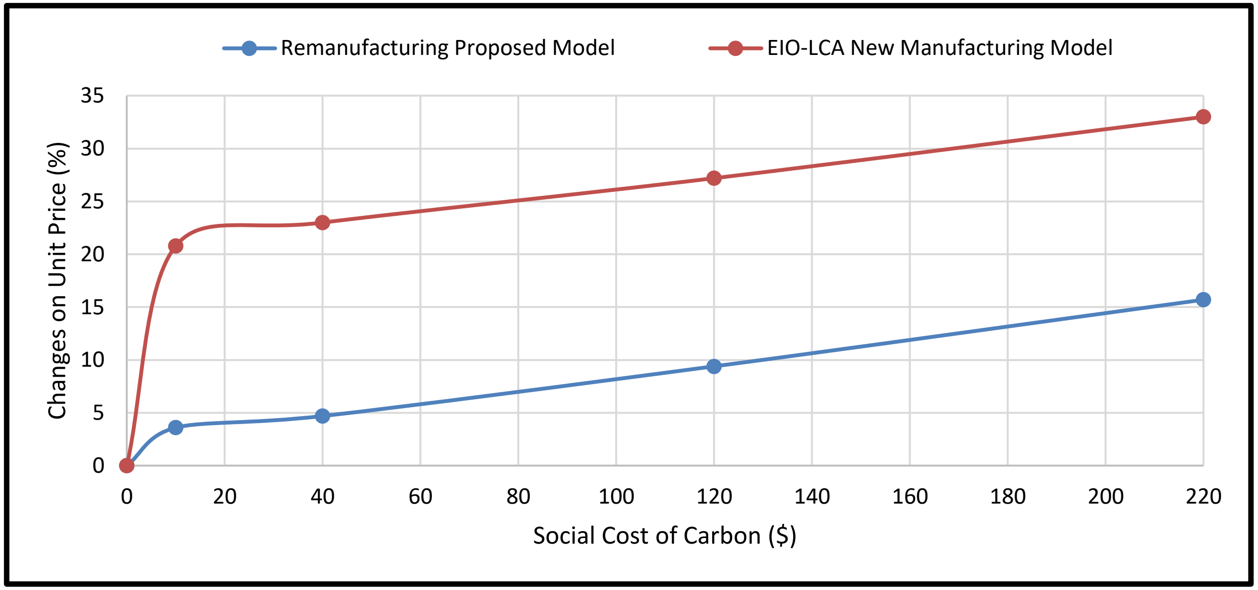


Figure 10: Social Cost of Carbon Effects on Unit Price

Figure 10 shows the effects of the SCC on unit price by comparing the developed remanufacturing model and the EIO-LCA manufacturing model for the new manufacturing producer prices.

Results: Deterministic Model with Relaxation Constraints

To examine the effect of carbon price uncertainty on supply chain network decisions, we considered 13 scenario groups for carbon pricing with identical demand scenarios.

Table 14: Case study results of the deterministic model for different carbon price scenarios

Carbon Price ($/ton)	Configuration	Total Carbon (ton)	Carbon Cost ($)	Total Cost ($)	Changes in Unit Price (%)	Emissions Improvement compared to the base scenario (%)
0	1	101	0	106962.00	0	0
10	1	99.00	990.00	108072.02	1.04%	1.98%
20	1	98.30	1966.00	108935.23	1.84%	2.67%
30	2	96.80	2904.00	109798.44	2.65%	4.16%
40	2	95.79	3831.60	110661.65	3.46%	5.16%
50	3	94.69	4734.50	111524.86	4.27%	6.25%
60	3	92.58	5554.62	112388.07	5.07%	8.34%
70	3	91.46	6402.48	113251.28	5.88%	9.44%
80	3	90.35	7228.08	114114.49	6.69%	10.54%
90	3	89.24	8031.42	114977.70	7.49%	11.65%
100	3	88.13	8812.50	115840.91	8.30%	12.75%
110	3	87.01	9571.32	116704.12	9.11%	13.85%
120	3	85.90	10307.88	117567.33	9.92%	14.95%

Results: Configuration 1-3

Figure 11 combined the unit price and emissions reduction performance changes at various carbon prices

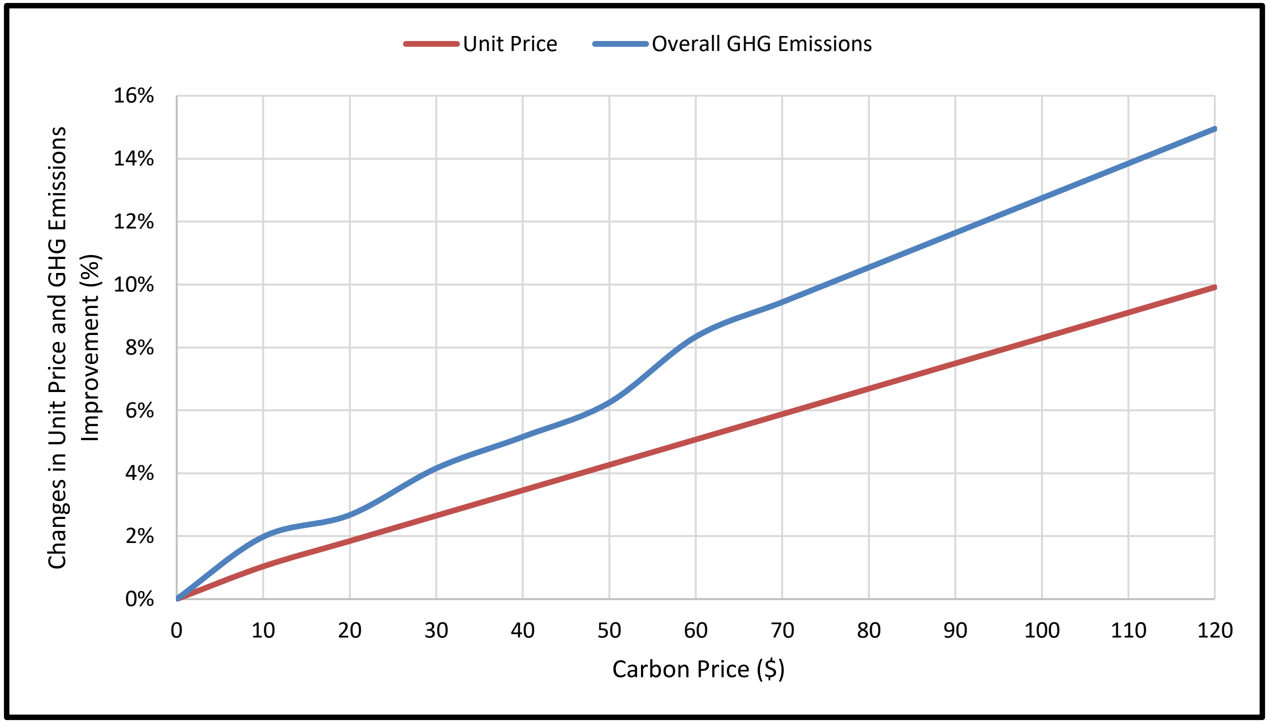


Figure 11: Unit price and emissions reduction performance changes at various carbon prices

Results: Configuration 1

Having no carbon tax in place (i.e., a carbon price of $0) and $10 and $20 prices results in "configuration 1".

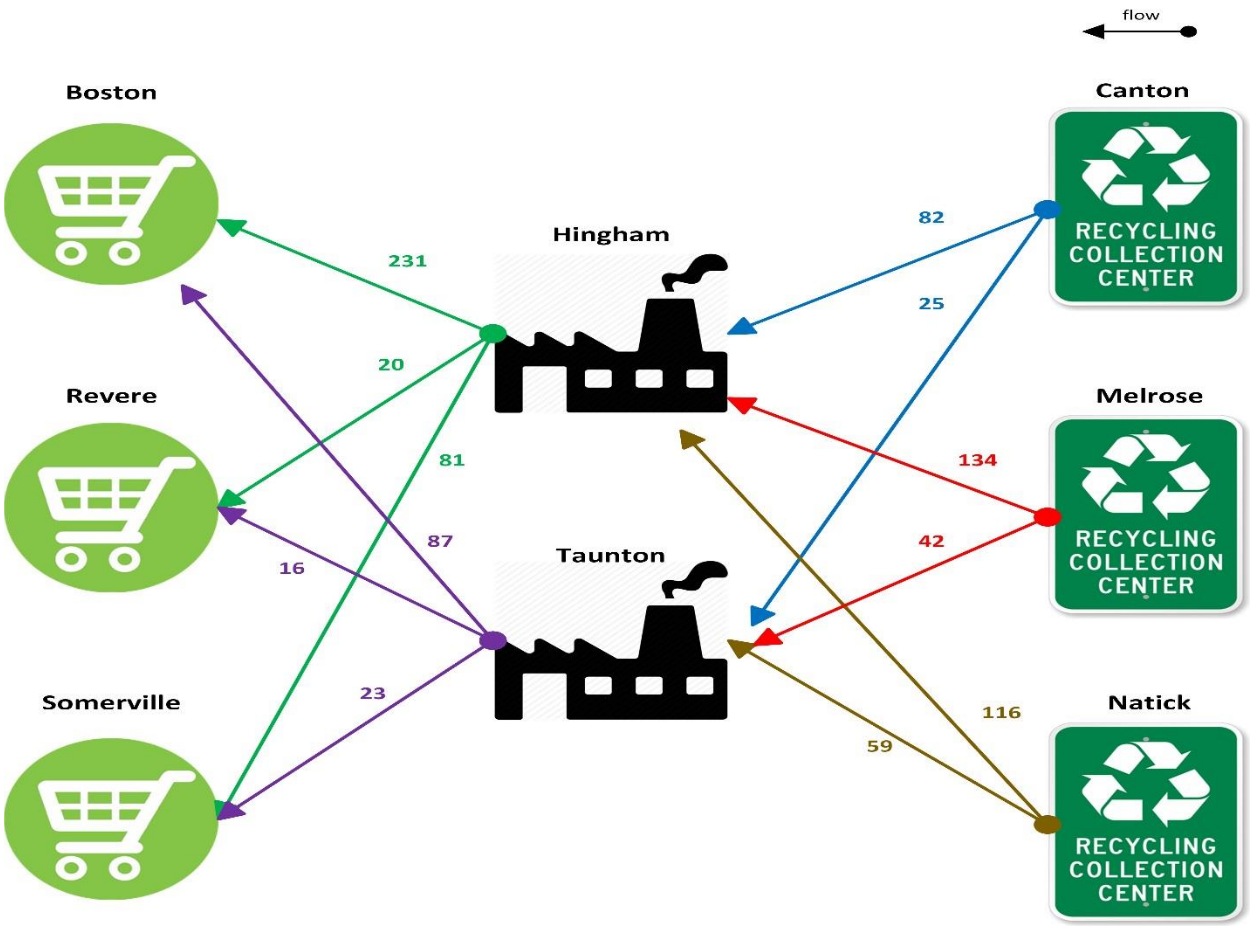


Figure 12: The supply chain network for Configuration 1

Results: Configuration 2

Introducing a carbon price of $30 per ton results in a shift from configuration 1 to configuration 2, which has fewer facilities and a greener supply chain configuration.

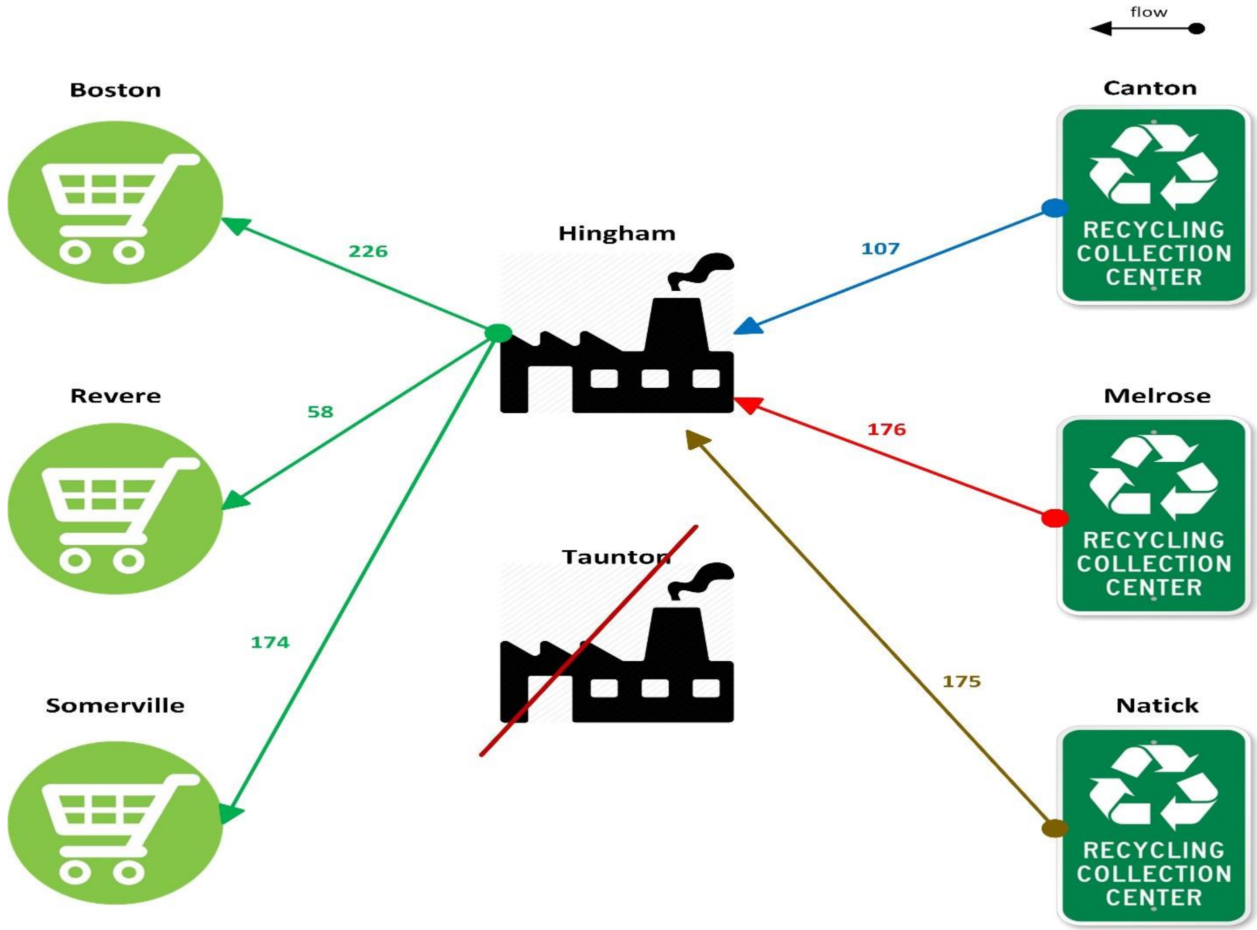


Figure 13: The supply chain network for Configuration 2

Results: Configuration 3

Configuration 3 has been chosen for a carbon price of $50 and above.

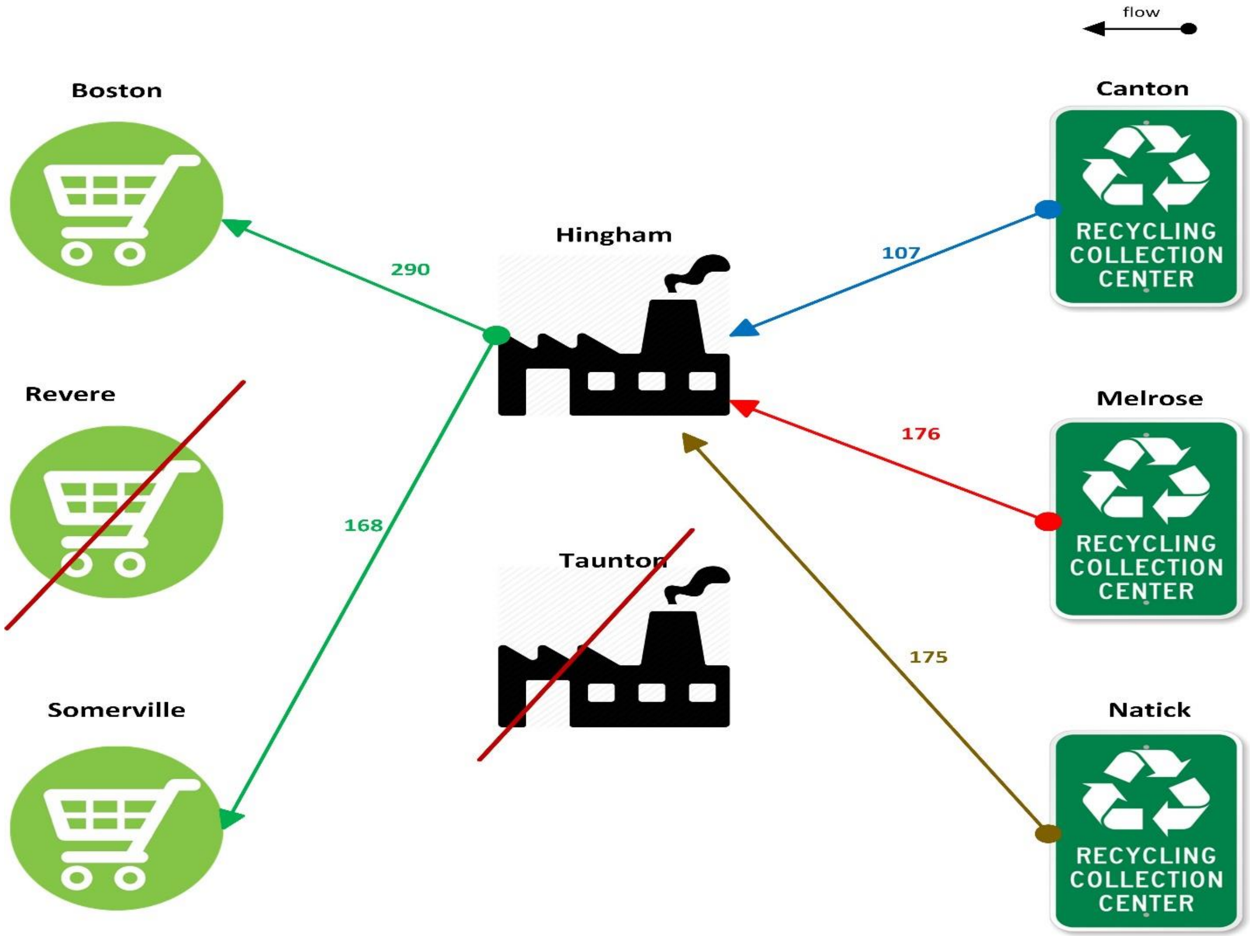


Figure 14: The supply chain network for Configuration 3

Results: Activities and GHG Emissions

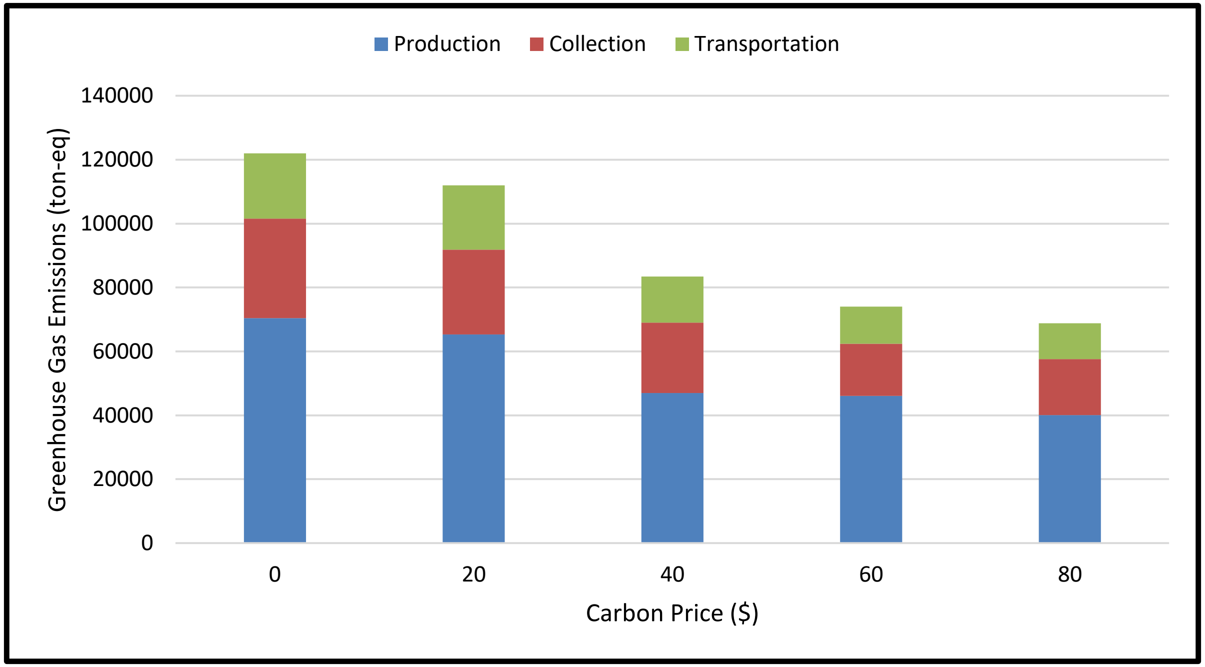


Figure 16: Generated carbon emission at various carbon prices

Results: Statistical Analysis

Table 15: Analysis of variance output summary

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	13	5.32E+10	4.1E+09	9.33	0.000
Transportation Cost	1	2.86E+10	2.86E+10	65.27	0.000
Energy Cost - fix	1	6933592	6933592	0.02	0.902
Energy Cost - variable	1	1.43E+08	1.43E+08	0.33	0.578
Rent Cost	1	4.02E+08	4.02E+08	0.92	0.356
Labor Cost	1	6414423	6414423	0.01	0.906
Social Cost of Carbon	1	4.54E+08	4.54E+08	1.03	0.328
Shortage Cost	1	3.43E+08	3.43E+08	0.78	0.392
Remanufacturing Cost	1	5.05E+09	5.05E+09	11.52	0.005
Mean demand rate	1	11585257	11585257	0.03	0.873
Retrieval Cost	1	2.85E+09	2.85E+09	6.49	0.024
Inventory Cost	1	1.28E+08	1.28E+08	0.29	0.598
Inventory level	1	7.69E+08	7.69E+08	1.75	0.208
Supply rate	1	3.96E+09	3.96E+09	9.03	0.010
Error	13	5.7E+09	4.39E+08		
Total	26	5.89E+10			

Results: Statistical Analysis

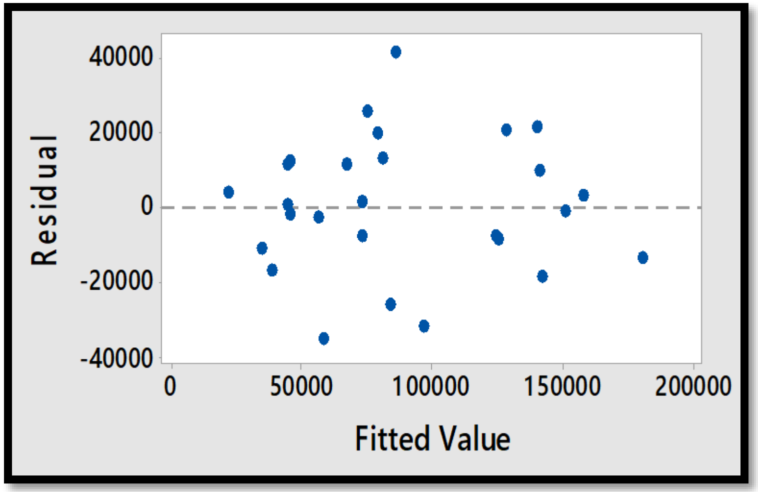


Figure 17: Fitted value

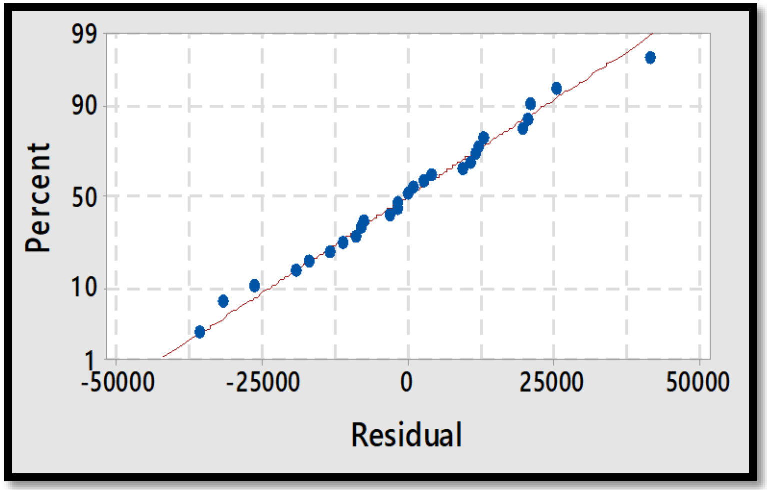


Figure 18: Residual

Figure 17 shows an ideal random scatter around a value of zero. This indicates that the residuals were homogenous.

Figure 18 shows that the residuals strongly support the normality assumption and appear to generally follow a straight line.

Study 3: Summary

- A deterministic equilibrium model was used to determine the effects of internalizing a cost of RSC GHG emissions into optimization models.
- Changes in optimal facility use, transportation logistics, and pricing/profit margins were all investigated against a variable cost of carbon.
- As carbon costs increase, the optimal RSC system undergoes several distinct shifts in topology as it seeks new cost-minimal configurations.
- A comprehensive study for quantitative evaluation and performance of the model has been done using Orthogonal Arrays.

Study 3: Summary

- Results were compared to top-down estimates from EIO-LCA models, to contrast remanufacturing GHG emission quantities with those from original equipment manufacturing operations.

- Introducing a carbon cost of $40/t CO_2 equivalent increases modeled remanufacturing costs by 2.7%, but also increases original equipment costs by 2.3%.

- The RSC configuration is sensitive to the carbon price.

- The assembled work advances the theoretical modeling of optimal RSC systems and presents a rare case study of remanufactured appliances.

Conclusion

Conclusion

- This dissertation develops novel multi-objective optimization models to inform RSC system design at multiple levels.

- The objective of this dissertation is to address the issues with of strategic "designing" and planning "tactical" levels of RSC.

- The decision-making problems that are faced by strategic planners of RSC include:
    - ➢ Collection center placement and capacity. Evaluation of the collection centers is the first stage in choosing the most profitable collection center.
    - ➢ Optimization of transport of EOL products while considering fuel and potential carbon costs, which has the focus of achieving transporting (used and remanufactured) products across a RSC while satisfying certain constraints that all fall under optimization of costs.

- After that, the decision maker would be faced by tactical level of problem that includes:
    - ➢ Pricing of remanufactured products, which has not been given any importance in the past but the scale and unique processes of transforming used and recycled products into "like-new" conditions, and recapturing the missing values that added to the products during manufacturing stage, have made the pricing an important subject of research.

Research Products

Journal Publications in Preparation:

- Alkhayyal, B., Gupta, S. M., and Eckelman. M. J. (2016). Reverse Supply Chain Network Design and Optimization Considering Carbon Cost. *Journal of Cleaner Production*.

Conference Proceedings:

- Alkhayyal, B and Gupta, S. M. (2015a). A Linear Physical Programming Approach to Evaluate Collection Centers for End-Of-Life Products. *Proceedings of the 2015 Northeast Decision Sciences Institute Conference*. Cambridge, Massachusetts.
- Alkhayyal, B and Gupta, S. M. (2015b). Optimal Pricing for Reusable and Recyclable Products Using Nonlinear Physical Programming. *Proceedings of the 26th Production and Operations Management Society (POMS) Annual Conference*. Washington D.C.
- Alkhayyal, B., Eckelman. M. J., and Gupta, S. M. (2016a). Managing transportation of products and greenhouse gas emissions in reverse supply chains. *Proceedings of the 27th Production and Operations Management Society (POMS) Annual Conference*. Orlando, Florida
- Alkhayyal, B., Gupta, S. M., and Eckelman. M. J. (2016b). Managing environmental issues in reverse supply chain. *Proceedings of the Institute of Industrial Engineers (IIE) Annual Research Conference*. Anaheim, California

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Appendix

Appendix