E-Commerce Based Closed-Loop Supply Chain for Plastic Recycling

By

Saikat Banerjee

Bachelor of Technology (B. Tech), Computer Science & Engineering
West Bengal University of Technology (2010)

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Signature of Author: ______________________________
Department of Supply Chain Management
May 2020

Certified by: ______________________________
Dr. Eva Maria Ponce Cueto
Executive Director, MITx MicroMaster's in Supply Chain Management
Director, Omnichannel Distribution Strategies

Certified by: ______________________________
Ms. Suzanne Greene
Program Manager, MIT Sustainable Supply Chains

Accepted by: ______________________________
Dr. Yossi Sheffi
Director, Center for Transportation and Logistics
Elisha Gray II Professor of Engineering Systems
Professor, Civil and Environmental Engineering

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ABSTRACT

The world is facing a grave plastic waste problem. It is not new that we hear about oceanic death and morbid landfills. Only 8% of all the plastic produced is recycled in the US. This grotesque situation has been worsened by the Chinese ban of plastic waste imports from the developed western nations as of 2018. In this research we assess the feasibility of a novel approach to using existing e-commerce reverse logistics channels to take back post-consumer plastic. We use product sales data to estimate the post-consumer plastic volume. We then, design a mixed integer linear programming (MILP) based optimization model to assess different take-back routes and calculate various operational costs. In addition to the optimization model we determine the feasibility of this process by considering cost offsets such as price of virgin plastics. After that, we conduct a scenario-based sensitivity analysis to understand systemic cost and overall profit. We used the results of these analyses to formulate the strategic recommendations for companies interested in promoting or implementing e-commerce-based recycling programs. Finally, we assess the greenhouse gas emissions and corresponding externality costs through this process and perform a qualitative assessment of the stakeholder networks vital to making such a system operational. In conclusion, our results suggest that in certain scenarios it is economically feasible to facilitate a take-back process for post-consumer plastic using existing e-commerce-based reverse logistics channels while maintaining minimal additional emissions in the process.

Thesis Advisor: Dr. Eva Maria Ponce Cueto
Title: Executive Director, MITx MicroMasters in Supply Chain Management
Director, OmniChannel Distribution Strategies

Thesis Co-Advisor: Ms. Suzanne Greene
Title: Program Manager, MIT Sustainable Supply Chains

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1. Introduction

Plastic waste is one of the primary global challenges facing humanity and our environment in the 21st century, creating intense inspection from consumers and industry into the life cycle of non-biodegradable plastic (Verma, Vinoda, Papireddy, & Gowda, 2016), (Narancic & O'Connor, 2019), (Chow, So, Cheung, & Yeung, 2017). The mismanagement of plastic waste is polluting the oceans, and this proliferation, if not checked, will add to the massive waste problem currently threatening the world (Jambeck et al., 2015), (Verma et al., 2016); (Tammemagi, 1999). In 2017, 35.3 million tons of plastic was generated in the US, out of which 2.9 million tons were recycled, 5.6 million tons were incinerated, and 26.8 million tons, a staggering 75.8%, were landfilled, (US EPA, n.d.). The incineration of the plastic impacts air quality, which further threatens the environment and poses a significant threat to human beings unless it is managed in a controlled environment, as in some of the Nordic countries (Fråne, Stenmarck, Gíslason, Lyng, & Løkke, 2014) and the UK (Jeswani & Azapagic, 2016). To decipher the magnitude of plastics being introduced into the environment and the oceans, we need to understand the lifecycle of plastics through processes such as, production, distribution, and waste management. Because of plastics' persistence in the environment, we must consider not only last year's production of plastic, but also all plastic production over time, and its infusion into the environment.

Plastics can be broken down into two categories: fiber and non-fiber plastics. The primary polymers that make up non-fiber plastics are Polyethylene (PE) (36% of global plastic production), Polypropylene (PP) (21%), and Polyvinyl Chloride (PVC) (12%), followed by, in smaller proportions, Polyethylene Terephthalate (PET), Polyurethane (PUR), and Polystyrene (PS) (<10% each). Approximately 70% of all of fiber plastic production can be attributed to Polyester, most of which is PET. These seven groups together amount to 92% of all plastics produced. Approximately

42% of all non-fiber plastics have been used for packaging, which is predominantly composed of PE, PP, and PET (Geyer, Jambeck, & Law, 2017). Packaging plastics accounts for 40% of all plastic produced, which is a staggering number and it is continuing to grow (Narancic & O'Connor, 2019).

Plastic production information helps us to understand the generation of plastic waste. Figure 1 shows the plastic used by different industries between 1950 and 2015. The packaging industry used the highest share of plastics and showed the biggest growth in production over time.

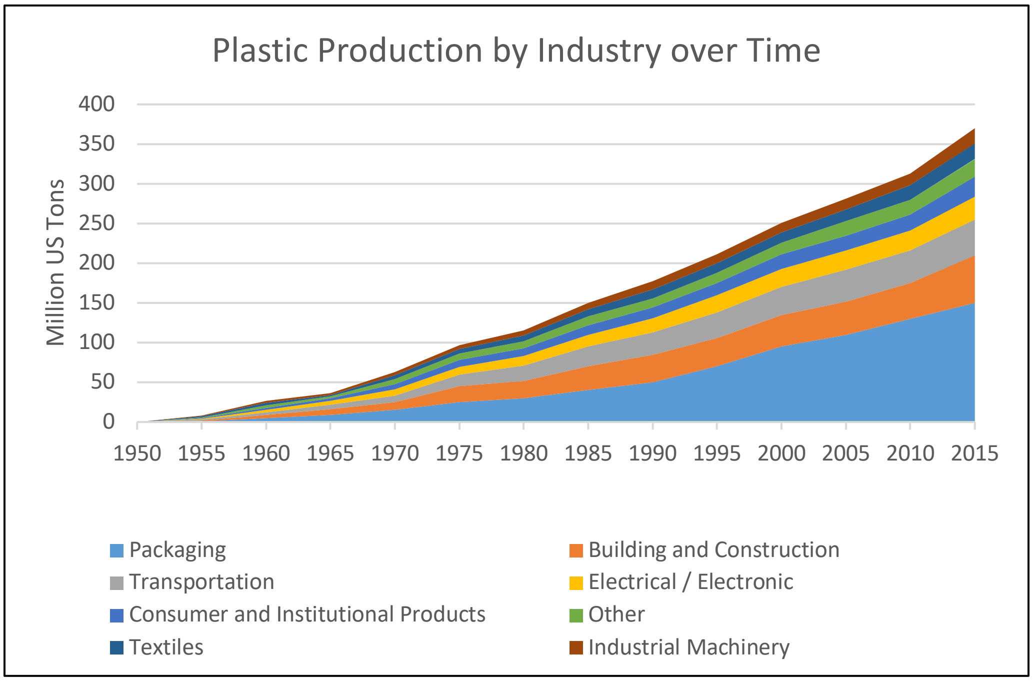


Figure 1. Distribution of primary plastic production in different industries. Adapted from (Geyer et al., 2017)

Figure 2 takes this a step further, showing the amount of plastic waste that has been generated by the same industries. The packaging industry dominates the plastic consumption market and thus the waste generation.

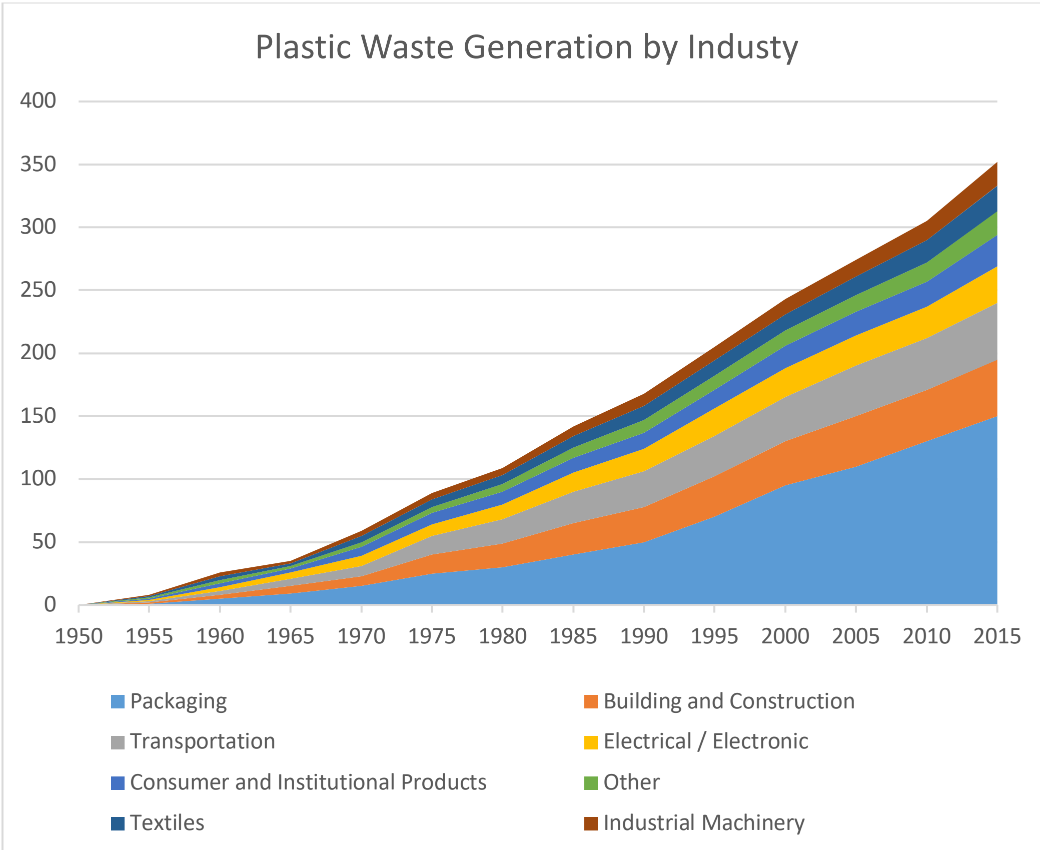


Figure 2. Spread of plastic waste production in different industries. Adapted from (Geyer et al., 2017)

A lifetime can be attributed to plastic packaging like the lifetime assigned to any products which are in use; Figure 3 shows distributions across industries in terms of product lifetimes. Ranging from toothbrushes to soap bottles, the plastics used in packaging have a particularly short lifetime, often less than one year due to the quick consumption period, coupled with the recurring nature of these products. These quick consumption times can be contrasted with plastics used in the construction, automotive or information technology industry, where the consumption period or lifetime can be in the range of years or decades. This dynamic has led plastics produced for packaging in consumer-packaged goods (CPG) to particularly contribute to the proliferation of global plastic waste.

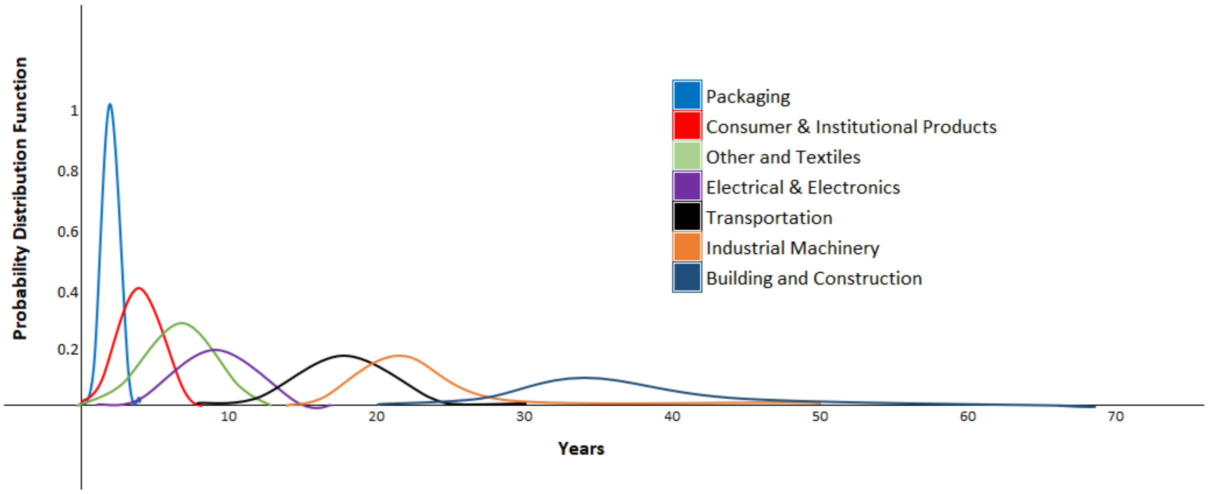


Figure 3. Probability distribution of product lifetime across industries (Geyer et al., 2017)

Therefore, there is a need to recycle or reuse the plastics in packaging and reduce the production of new plastics globally (Hopewell, Dvorak, & Kosior, 2009). In response to this crisis, many companies have started to evaluate new strategies to reduce plastic packaging waste, such as including more post-consumer plastic in their product packaging, for example, the Alliance to End Plastic Waste formed to start formalizing a solution to this global problem, and a sum of US $1.5 billion has been pledged by the members of this consortium towards fighting the plastic waste problem (“Alliance To End Plastic Waste,” n.d.).

One way to do fight the plastic problem is to improve the take-back of waste packaging in order to reuse it in new packaging. Current recycling systems are broken in the US and there are no effective mechanisms to take back plastic (Katz, 2019). Since China’s ban on taking plastic waste from the US, municipalities are facing an even larger problem as to how to get rid of the plastic waste that is produced in the form of municipal solid waste (MSW). A detailed 2020 study suggests that only a certain percentage of plastics is being recycled depending on the type of plastic, namely PET, high density polyethylene (HDPE) and PP (only 53%). The US doesn’t have adequate capability to recycle other types of plastics (John Hocevar, 2020).

Based on this literature review, we can say that most post-consumer plastics in packaging are of types PET and PP, and that we need an efficient mechanism to take them back for recycling. To effectively improve the take-back of post-consumer plastic packaging waste, there is a need to understand and model a closed-loop supply chain.

This thesis considers one mechanism that could contribute to this vision: a reverse flow of plastic packaging waste using existing e-commerce distribution channels. By building a model based on industry data and other predictable and measurable parameters, we were able to test the feasibility, efficiency, and cost-effectiveness of this system.

This thesis is structured into seven chapters, beginning with this introduction. In Chapter 2, we present the problem statement and objectives. Chapter 3 provides an extensive review of literature relevant to the proposed problem setting and methodology. Chapter 4 explains the methodology adopted in detail, including formulation of the network design model, and understanding the systemic cost equation. In Chapter 5, we outline the results from initial data analysis, the optimization model implementation and the cost analysis, and the scenario-based sensitivity analysis based on the results. In Chapter 6, we discuss the results from the scenario-based sensitivity analysis, a qualitative study of stakeholder initiatives, provide recommendations and explain the contributions. Finally, in Chapter 7, we conclude this thesis, discussing the assumptions and touching upon the road ahead.

2. Problem Setting and Objectives

The primary goal of this research is to design a model to facilitate an e-commerce-based reverse logistics channel approach to formulate a take-back of post-consumer plastic and thereby assess the feasibility of the same from economic, social and environmental points of view. When we order something online (say an Amazon order), in general, we expect the order to be delivered to our doorstep. In the door delivery process, the delivery van could, instead of leaving empty-handed after dropping the order, pick up post-consumer plastic and place it in a segregated section in the van, effectively initiating a reverse logistics process to a material recovery facility (MRF) directly or intermediary storage. This process can be made possible by any third-party logistics provider.

The objective is to first identify the different parameters in the system, such as, various costs, the volume of post-consumer plastic, and the price of different types of virgin plastic. The object is also to identify various actors of the system. We start by analyzing the volume, value and geographic distribution of the plastic sold by the CPG company. In terms of problem setting, we consider the US plastic sales data and focus primarily on distribution within the New England region, in states: Connecticut, Maine, Massachusetts, Rhode Island, New Hampshire, and Vermont. We study the costs in several tranches of operation. We perform this analysis using the sales data of products by a major CPG corporation as a case study, augmented by geographic locations and distance data of warehouses of prominent e-commerce providers and MRFs utilizing Google Maps API.

Then the objective of this research is to develop a network design model to assess the flow of the plastic take-back from a county to an MRF using a direct path or using a consolidation network, utilizing a warehouse (or distribution center) as a consolidator. Based on this model, we assess the overall cost that the company facilitating this process might incur.

The next objective is to propose a cost equation to assess the feasibility of the optimization model from the economic and environmental points of view. We assess the economic feasibility based on cost equation and determine the profit margin based on the analysis per county for the New England region. Then we assess the feasibility from the environmental point of view, by studying the CO_2 emissions as a result of this process and the cost of externalities by estimating the cost using standard carbon tax estimates.

Finally, our objective is to consider the stakeholder ecosystem required for this model to work. We identify the relevant stakeholders in the system and how each of the stakeholders could be incentivized both from economic and social responsibility points of view.

3. Literature Review

This chapter aims to provide background information and review the existing literature surrounding this project. This review includes:

(1) Policy directives pertaining to recycled plastic usage: Take-back policies for waste and hazardous materials like electronics differ around the world, and we examine the relevant policies that are in place for items like plastics that could impact the implementation of an e-commerce take back system. We look for examples where recycling is mandated by the governments, attempting to draw parallels for plastic packaging. We assess how similar policies can be designed for the plastic recycling regulations and how companies could implement those models.

(2) The intricacies of customer behavior towards the use of plastic and recycling of plastic packaging in CPGs: We ascertain that the customer is indeed concerned about the plastic pollution. We use this consumer concern to evaluate the likelihood for consumers to participate in the take-back process and assess the need to incentivize the consumer to return the post-use plastic packaging to the retailer or the manufacturer.

(3) Potential uses of post-consumer plastics: We assess the recycling potential of plastic packaging by categorizing the various types of plastics based on their potential recyclability. We understand the potential uses to identify economic opportunities through the reuse, recycle and remanufacturing methods, we discuss in Section 3.3.

(4) Existing reverse logistics mechanisms for products in other industries: We understand how the take-back process through reverse logistics works for products in other industries like the textile and electronics industries. Studying the existing reverse logistics mechanisms used for recycling in recyclable substances would enable us to draw similarities in processes.

(5) Uses of the e-commerce reverse logistics channels for take-back: We study the feasibility that e-commerce can be used to take-back plastic. This study of the existing e-commerce reverse logistics channels helps us understand, how the existing flow of post-consumer products or consumer returns can be fused with the post-consumer plastic take-back. We, also, verify that this system has not been tried thus far and this is identified as the gap in the existing literature.

(6) The different types of costs: We focus on the different types of costs involved in the several mechanisms affecting the take-back flow. As a last step, we assess the cost of the operations of the take-back and the purchase cost of virgin and recycled plastics and how this makes the whole process economically feasible. This assessment of different costs helps us formulate the profit margin of the facilitating entity that enables the process recommended in this paper.

3.1 Policies on Plastics

There are several directives in place for several hazardous products spanning different industries. End-of-life electronic products can result in hazardous e-waste, and hence there are numerous directives for take-back of the products by the manufacturers. For the purpose of this thesis, we draw parallels from the policy directives around e-waste take-back and look for similar policy directives or the potential for such directives for plastics in the United States.

3.1.1 EU Directives on Electronic Items Take-Back

The EU has strong laws for the take-back of the end-of-life post-consumer electronic item, and it is the producer's responsibility to arrange to collect the items. This is known as the Extended Producer Responsibility (EPR), and the boundaries of the same have been debated. These laws have forced the companies to primarily think about four different strategies: (1) forming a take-back network; (2) rethinking product design; (3) setting up a closed-loop supply chain; and (4) adopting new technologies and business models. EU models generally stipulate what producers must spend on the take-back of the products based on the market share of the producer. A good model of this can be found among companies like Hewlett-Packard (HP Inc.), Sony Corporation, Braun GmbH, and Electrolux AB. Apart from the cost incurred by the take-back of end-of-life products from the customer, the costs for recycling are also borne by the producers based on the market share of the producer. A further discussion stems from the context of implementation of EPR. These laws do not encourage product innovation, which in turn reduces the need for recycling. A study has suggested that producers pay for a share of the take-back based on the percentage of their products which require take-back and recycling. This would encourage a long-term focus on product innovation so that the need for the take-back is minimized (Atasu & Van Wassenhove, 2011).

3.1.2 US Directives on Electronic Waste

Federal laws for take-back of electronic waste do not exist in the US; however, 22 out of the 50 states have passed e-waste bills that mandate producer responsibility (Atasu & Van Wassenhove, 2011). Some states in the US have implemented EPR-type regulations. In the US few states that have mandated EPR for batteries, such as New Hampshire's ban on disposal and incineration of batteries (*New Hampshire Code of Administrative Rules*, 2017). EPR helps shift the costs from the municipality to the producer, while at the same time enabling value extraction if possible from the end of life.

3.1.3 EU Directive on Plastic

The EU effectively banned single-use plastic (Brussels 2019) in 2019 due to the ubiquitous nature of the single-use plastic and its proliferation by short-term usage which causes pollution. The EU member states have sparingly adopted this directive and are forming implementation and enforcement strategies to combat the single-use plastic.

3.1.3.1 The EU directive is a step towards establishing a circular economy where the design and production of plastics and plastic products fully respect reuse, repair and recycling needs and more sustainable materials are developed and promoted. There are highly negative impacts in terms of environmental, health and economic aspects from the use of certain plastics. The environmental impact of toxins can cause health problems both in animals and humans (Verma et al., 2016). Cancer incidents near MSW incinerators are also important factors to consider while planning to mitigate plastic waste by burning (Elliott et al., 1996). Such negative impacts require the setting up of a specific legal infrastructure to effectively mitigate these negative impacts (General Secretariat of the European Parliament and of the Council, 2019).

3.1.3.2 The existence of policies that promote circular mechanisms to facilitate take-back of toxic and hazardous products both directly and indirectly are in effect in the EU. The policy triages effective non-toxic multi-use products, as opposed to single-use products, to reduce waste generation and thereby mitigate pollution through waste. (General Secretariat of the European Parliament and of the Council, 2019)

3.1.4 US Directives on Plastic Usage

No such federal laws exist so far in the US, but there is a strong inclination to ban single-use plastic products like straws and plastic bags. For example, Boston has started the use of reusable plastic bags and customers have been charged at least 5 cents for a reusable plastic bag (Phillips, 2018). There are proposed federal policies like “Save Our Seas Act 2.0”, which aims at improving response to marine plastic and also contribute at an international level to control the advent of new plastic into the oceans. At the time of this writing, this act has passed through the final stages of the Senate committee on Commerce, Science and Transportation (Whitehouse, 2019). At the time of writing this paper, another policy, “Break Free From Plastic Pollution Act” has been placed in the Congress, and is yet to be approved. This policy establishes the following guidelines: (1) minimum reuse, recycling, and composting percentages of products, and (2) increasing the content of recycling material in new product manufacturing. This act would also encourage producers to put easy to read labels and also if the product is reusable, recyclable or compostable (Udall, 2020).

3.2 Consumer Response to Plastic Recycling and Take-Back Programs

The consumer is more willing to pay (WTP) towards plastic recycling costs than they are for aluminum, glass and cardboard cartons. The customers' WTP is assessed through the embedded recycling cost in the product. However, consumers living in "bottle-return states" do not express a higher WTP towards recycling costs. This is because of the expectation of bottle return in the "bottle-return states" makes the inherent higher prices evident in the price for the initial product purchase (Klaiman, Ortega, & Garnache, 2016). Environmentally friendly products can have a positive impact on consumer choices, and green packaging drives consumer behavior sufficiently to attract environmentally responsible customers to purchase greener products (Rokka & Uusitalo, 2008). This customer behavior leads to the following: that consumers would think positively about recycling of plastic and would participate in the take-back of the plastic packaging of CPG products.

3.3 Recycling and the Potential Use of Collecting Post-Consumer Plastic

We discuss the potential use of post-consumer plastic and outlines the benefits of recycling from the circular economy standpoint.

3.3.1 Drivers of Sustainable Plastic Solid Waste Recycling

At the household level the driver of recycling MSW is primarily to reduce the creation of waste that doesn't decompose (Tonglet, Phillips, & Bates, 2004). At a psychological level, minimizing waste creation is more powerful to adhere to for the consumer than a local government mandated requirement to recycle, and thus programs geared towards exciting monetary opportunities to reduce waste pushes households to recycle more and also create less waste (Tonglet et al., 2004). Consumers usually need to be educated to see the MSW as a resource with an economic value attached to it, however in the US the benefits of recycling have long been promoted.

3.3.2 Economic and Environmental Motivation for Fossil Fuels

As virgin plastic is typically created from fossil fuels, recycled plastic can reduce the manufacture of virgin plastic, thus saving petroleum, natural gas, and other byproducts. Also, environmental protection through reduction of plastic manufacturing triggers consumer sentiments and awareness towards being sensible about plastic use and plastic recycling. Moreover, both consumer and producer responsibility rules and regulations have also been identified as drivers of solid waste management systems from the economic, social and environmental aspects (Mwanza & Mbohwa, 2017). As an economic driver the take-back plastic can be recycled and reused in remanufacturing processes, reducing raw material costs in the process. On the environmental side, regulation on plastic waste collection involves large-scale social endeavor directed towards an environmental cause, as societies come together to facilitate recycling and be an active participant in the process. Similarly, as an environmental driver, the regulations protect the environment (and society) from the toxins released by plastic waste when landfilled or incinerated.

3.3.3 Future Use of Post-Consumer Plastic

A theoretical study suggests that any product take-back can have multiple benefits for the manufacturers, such as (1) a source of inexpensive components and materials; and (2) avoidance of disposal and incineration costs to be incurred by the producer based on EPR policies discussed in Section 3.1.2; and (3) a buy-back opportunity for manufacturers to sell new products, such as polyester-based clothing material that is very popular for athletics and other sports. New products could also entail substituting recycled plastic in products originally made from virgin plastics. Thus, the study bolsters our assumption that there will be a monetary value associated with product recovery by the producer. (Thierry, Salomon, van Nunen, & van Wassenhove, 1995)

3.4 Use of Reverse Logistics in Take-Back for Recycling

After the discussion on plastic take-back and its benefits in prior sections, we now study where reverse logistics has been used for returns and take-back of products. We look at textile and battery take-back as examples to draw parallels and similarities to our model of the plastic take-back.

3.4.1 Similarities of Post-Consumer Plastic Take-Back for Recycling with Textile Take-Back

Processes that are like those in a proposal to use reverse logistics of textile (Bukhari, Carrasco-Gallego, & Ponce-Cueto, 2018) can be understood, and expanded, for plastics. The way each type of plastic is collected from the end consumer determines how complex the system might be designed. Expanding upon a general consolidation-based network design, we can understand how e-commerce (and other reverse logistics channels) can be used to take back the plastic to a sorting location. Furthermore, the use of upcoming artificial intelligence (AI) based computer vision technologies like AutoSort, which uses robotics to sort between visibly different substances (Hahladakis & Iacovidou, 2018). This can be used to sort different types of plastics, for example, this technology can be used to segregate bottles (PET) and caps (PP). This process further helps the recycling processes, as the process to recycle PET is different from PP.

3.4.2 Similarities of Post-Consumer Plastic Take-Back for Recycling with Battery Take-Back

Process similarities of post-consumer plastic take-back for recycling with battery take-back is studied in this paper. This research uses a mixed-integer linear programming (MILP) based network design model from the consumer location to a sorting center and then to a recycling plant can be assessed as one of the potential mechanisms for post-consumer plastic take-back. This can be understood as a mechanism that drives e-commerce-based reverse logistics, where a return is picked up from an end-consumer, consolidated at a warehouse or a distribution center and then sent to the manufacturer (Ponce-Cueto & González-Manteca, 2012). We can leverage a similar model while designing the take-back of post-consumer plastic for recycling.

3.5 Use of E-Commerce in the Take-Back Process

In this section, we study e-commerce, primarily from the reverse logistics standpoint. We understand customer returns and the process of e-commerce take-back to facilitate returns. There are several models, such as a consumer-based return aggregator (e.g., Amazon Hub Locker), direct pickup (e.g., UPS pick-up) from consumer locations, and consumers sending the product back through common logistics providers (e.g., FedEx, UPS, US Mail and others).

3.5.1 E-Commerce Returns

E-commerce reverse logistics channels has been used to facilitate the customer returns process primarily. However, it has also been used to support the following: (1) competitive advantage – efficient handling of returns of the products in the e-retail space can generate large cost savings; (2) product reuse – effective use of reverse logistics for the return of the product facilitates reuse. This enables value extraction from the product, by direct reuse or by generating value by disintegrating the parts when the returned product is put through the remanufacturing process; and, (3) environmental impact – adhering to the EPR in the EU to reduce the volume of waste (Kokkinaki, Dekker, de Koster, Pappis, & Verbeke, 2002).

3.5.2 Process of the E-Commerce Take-Back

To understand the e-commerce-based take-back process it is important to understand the material flow of the product in such a system, as Figure 4 shows.

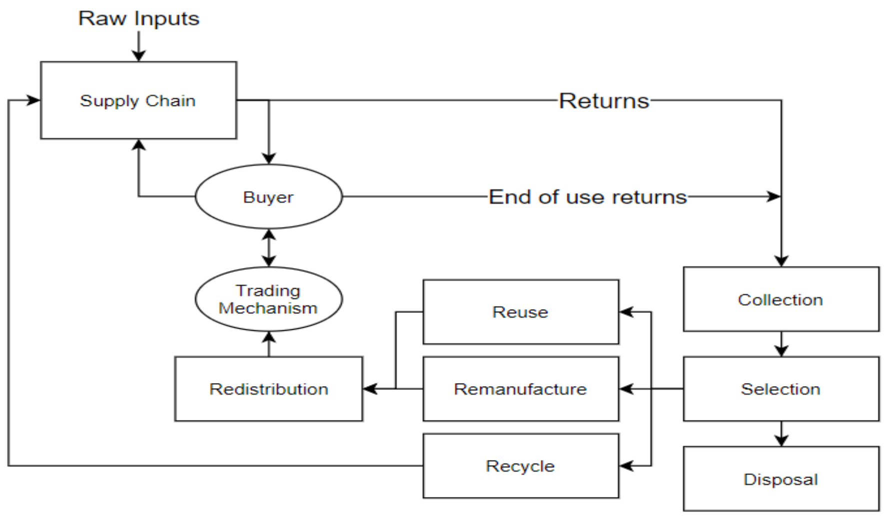


Figure 4. Classic reverse logistics flow adapted from (Kokkinaki, Dekker, De Koster, Pappis, & Verbeke, 2002)

The supply chain of the product flow is important to understand to understand the reverse flow of the products. The forward flow starts after initial product manufacturing. The product flows from the factory to warehouses or distribution centers, where it is stored to be further shipped to stores or directly to customers (in case of e-commerce). Finally, the product reaches the customer through retail or e-commerce channels. The reverse logistics process starts when the customer initiates a return on a used or unused product. The product is either picked up from the customer location or the customer drops the product off at a drop-off location. The product is then carried to a consolidation center, usually a warehouse or a distribution center. The product undergoes inspection through a sorting and selection process. Then, after sorting and selection, it is determined which of the returned products will be reused, recycled or remanufactured, or which products will be disposed of. Based on this decision the products move to redistribution after the completion of the aforementioned processes (Kokkinaki et al., 2002) (Govindan, Palaniappan, Zhu, & Kannan, 2012).

3.6 Aspects of Cost in the Take-Back Mechanisms

Finally, in this section of the literature review, we study the costs of operations. The costs of operations signify the various component costs to enable a take-back process using reverse logistics channels. We also understand the various other costs in terms of recycling processes, and operational costs in the MRFs.

3.6.1 Cost of Reverse Logistics Modes to Decide Optimal Take-Back Channels

To utilize the reverse logistics channels to facilitate take-back it is important to understand the cost in each of the reverse collection channels. Every step of the supply chain incurs cost. Focusing primarily on the reverse logistics supply chain the costs can be summarized as pickup cost, transportation cost (primary leg, middle-mile and last-mile), sorting and handling costs at the warehouse, storage cost, and other miscellaneous costs such as IT, human resources, etc. The optimal reverse logistics route is typically selected based on the minimum total cost incurred in that route as compared with the total cost incurred in all other routes. Studies show that, in the case of products manufactured by Apple Inc., HP Inc., and The Eastman Kodak Company, the choice of the optimal reverse logistics channel strongly depends on the cost of the channel, type of the product, and the volume of units sold. Because of the economy of scale, the take-back through the retailer is more cost-effective; however, in the case of fragmented dissemination of products and brands, a manufacturer take-back is more cost-effective (Atasu, Toktay, & Van Wassenhove, 2013). Even though we can pull similarities from this outcome we cannot comment on whether the same pattern will be applicable in case of the plastic product take-back; more research is needed to better understand this dynamic for plastic (Klausner & Hendrickson, 2000).

3.6.2 Cost of Recycling

There has been limited research regarding the cost of recycling processes in the US. The cost of recycling is dependent on several variables, such as collection techniques, frequency of collection, equipment used, and the type of material that is collected for recycling (Hegberg, Hallenbeck, & Brenniman, 1993). This study also showed approximate costs of collection of different types of plastic per household per year and the breakdown of the recycling rates. However, this research is dated, from 1993, and thus, the cost figures mentioned in the study would not be relevant in the current scenario and the cost of recycling would be needed to be considered from recycling plants' current price quotations.

3.7 Conclusion of Literature Review

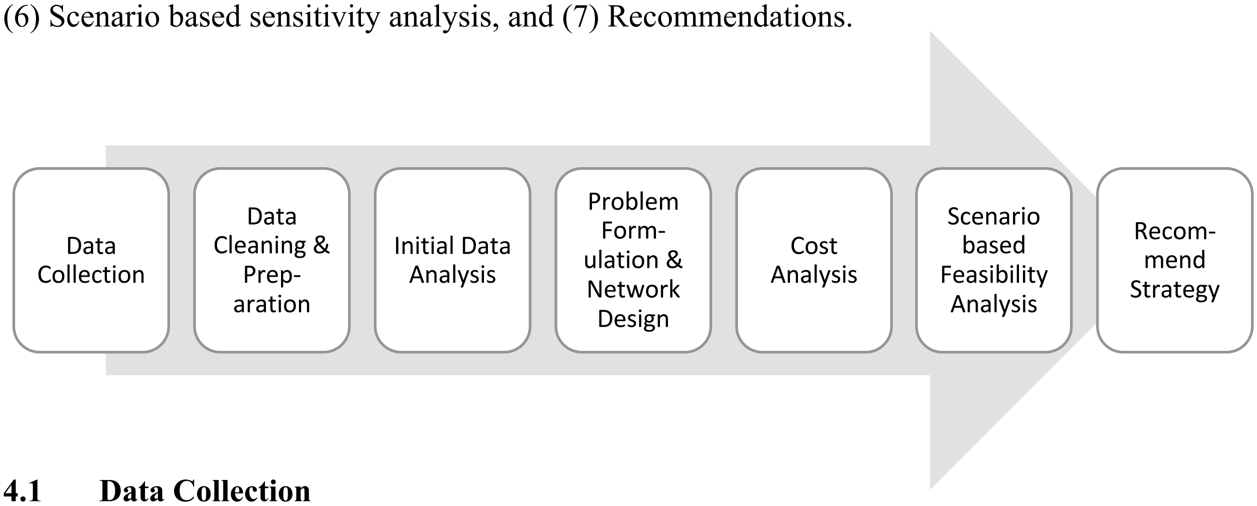
In the literature review, we found that there are no federal policies for plastics in the US, however, the general household is more attuned to this global problem and shows more empathy towards plastic recycling and willing to pay more for plastic packaging in lieu of recycling costs. We studied the potential of the plastic take-back and we discovered several opportunities that post-consumer plastic can uncover. We found that take-back policies for different products have worked out well in the past using reverse logistics channels. We also, found that studies have been conducted to understand several implications of product take-back, some stipulated by laws, others to generate value from the post-consumer product. In the case of plastic, post-consumer plastic can be a viable option for value generation for companies that facilitate the take-back process.

The literature review presented in this section shows that the literature and research on using e-commerce models for plastic take-back is scarce. The gap in the literature is that the assessment of using e-commerce channels for the take-back of post-consumer plastics generated from CPG products has not been done. This gap has been identified in the literature review done in this research. This research, thus, aims to shed light on the feasibility of such a model using the e-commerce based reverse logistics channels.

4. Methodology

In the literature review we identified the gap in the literature regarding the use of e-commerce channels to facilitate the take-back of plastic from consumer locations back to MRFs. We also studied how a reverse logistics network has been used to facilitate the take-back of similar waste generating products.

In this section we define the methodology and the steps we took in conducting this research. This section can be broken down into seven actions: (1) Data collection; (2) Data preparation; (3) Initial data analysis (4) Problem formulation using a network design approach; (5) Cost analysis (6) Scenario based sensitivity analysis, and (7) Recommendations.



4.1 Data Collection

In this step we collected data from several sources regarding the following 10 topics:

(1) CPG product sales information – This gave us the total plastic waste generation by the CPG company in a year through the number of products sold via and the weight of each plastic type in tons;

(2) CPG product market share information – This product-specific market share information helps us to estimate the overall US market for that product, making it useful for calculating the total weight of plastic generated by the overall CPG industry by plastic type in tons;

(3) Census information regarding population ratio per county – This data point allows us to estimate the population ratio of every county on the US; and based on this information it will be easy to estimate the consumption per county. [Data source: Census.gov];

(4) Census information regarding per-capita income per county – This data point allows us to skew the plastic consumption information further to understand the actual consumption per county more closely. This data point is applied over the population ratio metric to come up with the final plastic waste numbers for every county. [Data source: Census.gov];

(5) County centroid points – County centroid points are latitude-longitude (Lat-Long) values that generate a central point in the county based on data provided by Google Maps API. This data is used to estimate the transportation miles for the local distances within the county. Data source: Google Maps;

(6) MRF locations across the US – This data gives us the Lat-Long values for all the MRFs which were further used to calculate the linehaul distances. [Data source: ("Residential MRFs - The Recycling Partnership")];

(7) Amazon warehouse locations across the US – This data point also, helps us to calculate linehaul distances between county centroids and MRFs. We have used Amazon as a case study here due to the number of warehouses in the US and because Amazon is among the most prominent e-commerce actors in the US. [Data source: ("Locations of Amazon Fulfillment Centers in USA - Forest Shipping," n.d.)];

(8) Operational cost information – Operational cost information takes into consideration different costs that incur in different tranches of the operations. This cost information can be broken down into several other data points such as (a) Cost of Transportation (US $/mile), (b) Cost of Storage

(US \$/lbs.), (c) Cost per Stop (US \$), (d) Cost of Recycling (US \$/ton), (e) Cost of Emissions (US \$/ton-CO_2). All these costs are relevant to understand the different scenarios and overall benefit of using the take-back process for post-consumer plastic;

(9) Vehicle information – This data point specifically points towards understanding the various types of vehicles, for example small e-commerce delivery vans with a capacity of 3,500 lbs. and long-haul trucks with a capacity of 720,000 lbs.; and,

(10) Emission information – In this data point we estimate the total grams of greenhouse gases, using the standard unit of CO_2-equivalents (CO_2e), generated by different types of vehicles using the accounting methodology and average industry data for US specified within Global Logistics Emissions Council Framework. In our research we primarily focus on small vans (vehicle Type 1) and large trucks (vehicle Type 2) and consider both the weight of plastics transported and the distance traveled.

This step enables us to move to the Data Cleaning and Preparation phase, which will make the data ready for analysis.

4.2 Data Cleaning and Preparation

After data collection, we prepared the data by performing the following steps:

(1) Data cleaning – We eliminated missing data from the collected datasets, nameless from the sales information and census information;

(2) Unit normalization – We performed unit normalization across our entire datasets to curtail disparities between data collected through different channels. For example, we changed all the weight values to US tons and smaller units to pounds similarly, we changed all the distances to miles. Furthermore, we normalized all the dependent variables that depend on the weight and

distance values. For example, we changed the Cost of storage from $ per kg to $ per pound and the Cost of Transportation from $ per km to $ per mile;

(3) Calculating overall US sales of CPG products – As discussed in Section 4.1 (Data Collection) we calculated the overall US sales of the products sold by the CPG company by dividing the CPG Company sales with their market share. This number gives us the total weight of plastic in the products sold by the entire CPG industry. This also enables us to cluster the weight as derived from sales based on plastic type to get the tonnage generated by specific plastic classes;

(4) Normalization on Sales Data – As discussed in the Section 4.1 we performed a normalization operation on the overall US CPG sales data by plastic class by multiplying the tonnage with population ratio and the income skew. The income skew was calculated by taking a weighted average of county-specific per-capita income over the per-capita income of all of US;

(5) Preparing Distance Data – From the Lat-Long values collected for county centroids, Amazon warehouses, and MRFs as discussed in Section 4.1 we calculated the actual distances by using the Distance Matrix API provided in the Google Maps API suite. We wrote software code to invoke the API iteratively to get a Cartesian product of distances against all the Lat-Long values, as discussed in Section 4.1;

(6) Preparing Emissions Data – we parameterized the emissions data based on the values from the data collected for two vehicle types mentioned in Section 4.1.

Upon completion of the data cleaning and preparation we could move to the initial data analysis phase.

4.3 Initial Data Analysis

After the completion of data cleaning and preparation we performed an initial data analysis, including data sensing, to understand the different clusters in which the data is spread out. For example, we found the spread of the plastics collected over different plastic classes as shown in Figure 5.

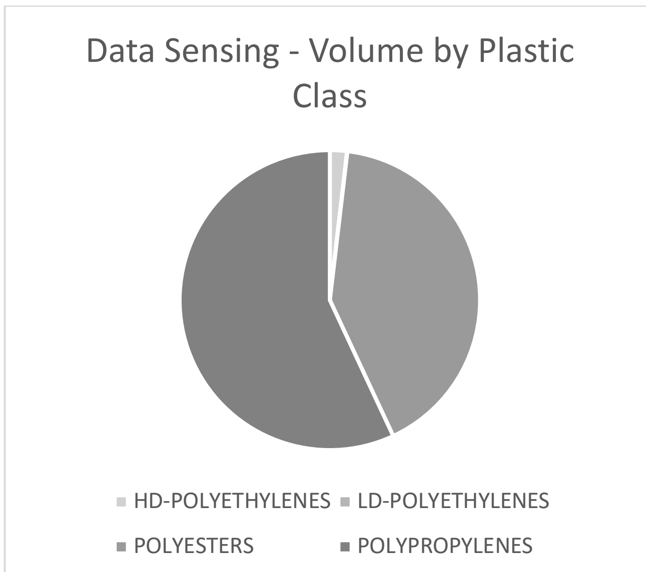
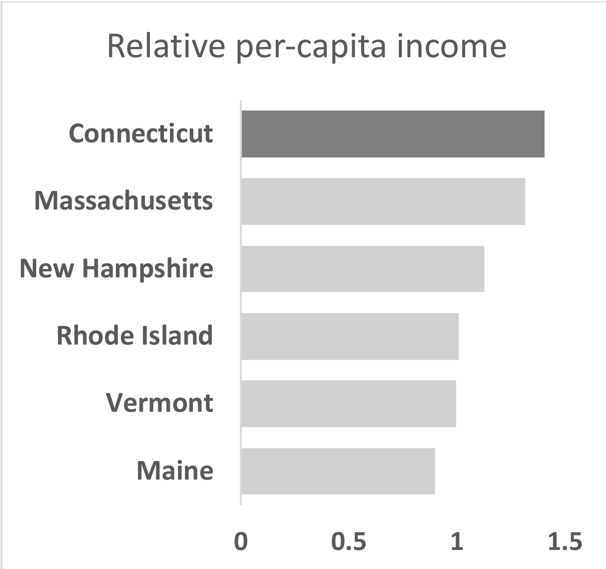


Figure 5. Volume of plastic sold by CPG companies in all of US by plastic classes

Similarly, we tried to understand the relative per-capita income and population ratio for all the states in the New England region, as shown in Figures 6 and 7.



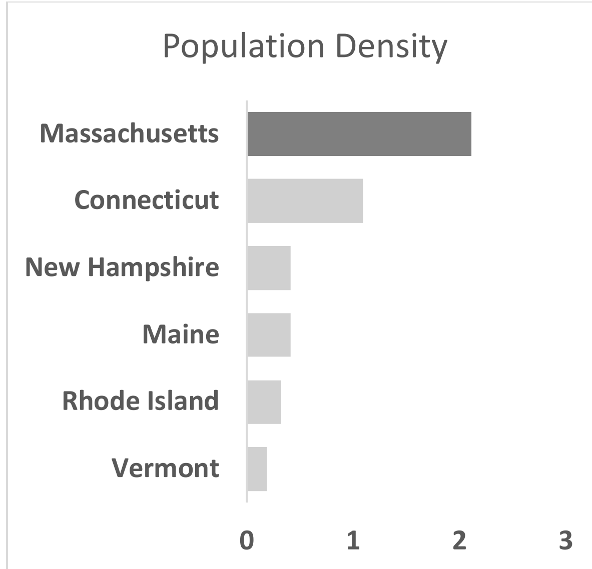
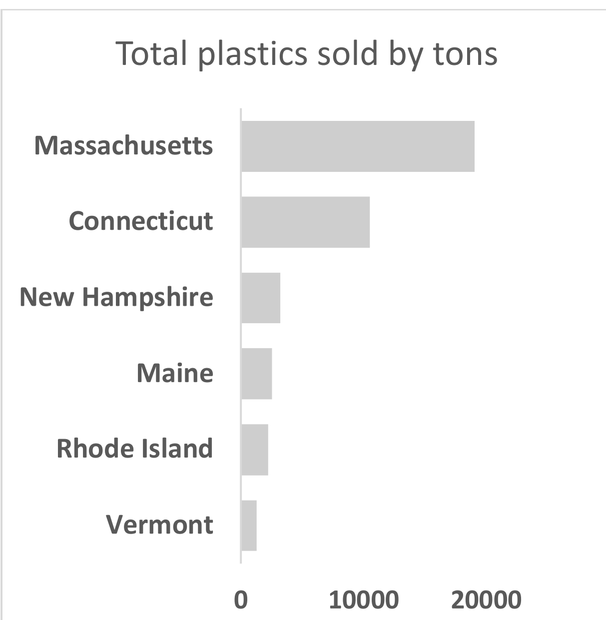


Figure 6. Per capita income for New England states relative to per capita income in the US

Figure 7. Population ratio of New England states relative to US population

We understand how the plastic weight is spread across different states in the New England area as shown in Figure 8 and investigate the plastic data through a further breakdown analysis by plastic classes as shown in Figure 9.



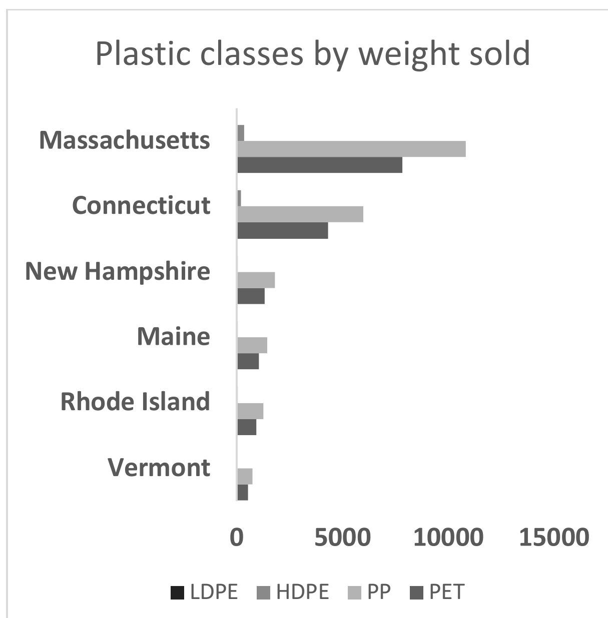


Figure 8. Total plastics sold through CPG products in New England states

Figure 9 Plastic sold by plastic classes in New England states

We also plot all the physical locations of county centroids, Amazon warehouses and MRFs on the US map based on their Lat-Long values as discussed in Sections 4.1.5, 4.16 and 4.1.7.

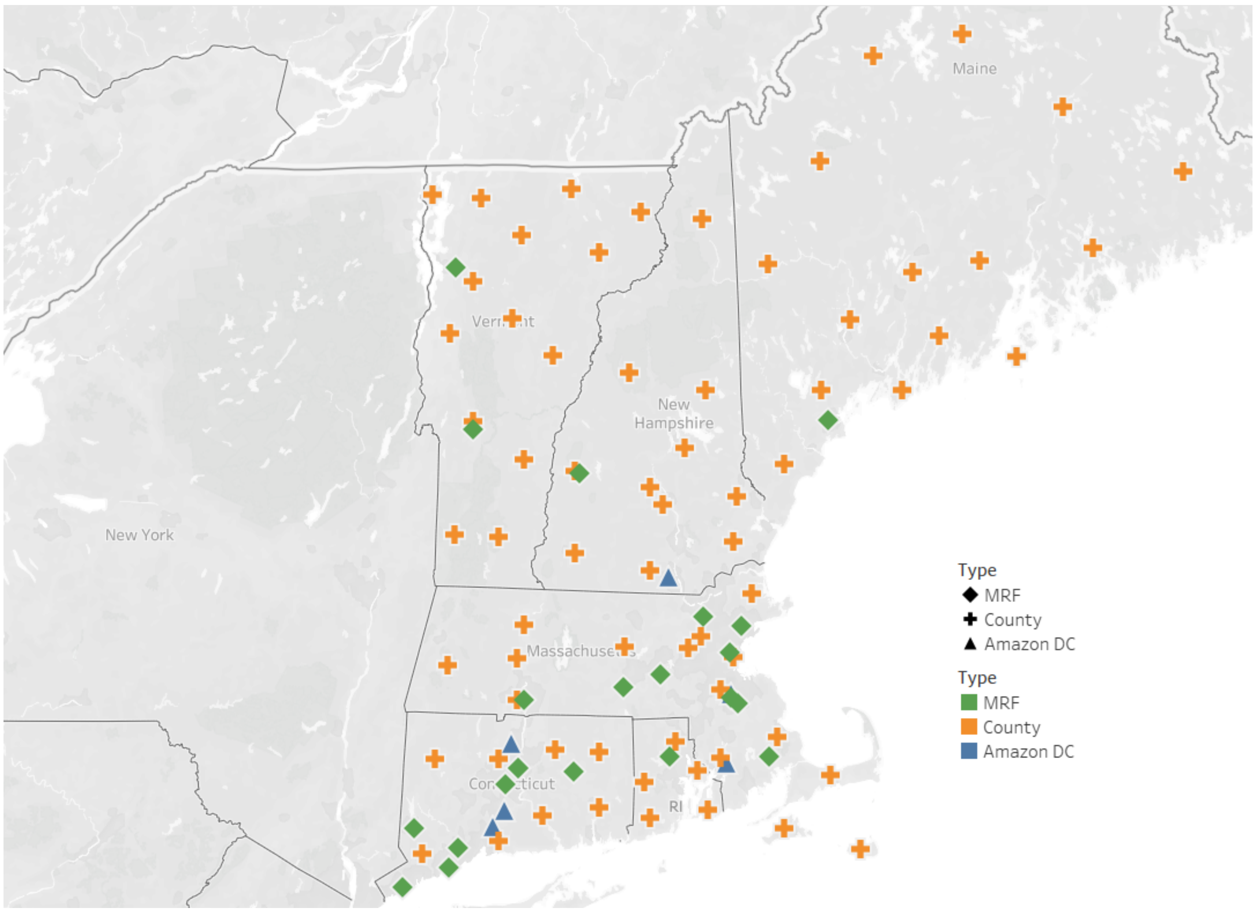


Figure 10. Lat-Long plot of County centroids, Amazon Warehouses and MRFs in the New England area

After the initial data we formulate our model using the network design approach, as described in Section 4.4.

4.4 Problem Formulation Using A Network Design Approach

After completing the initial data analysis, we used what we learned to formulate our model using a network design approach.

In this formulation we designed a network design optimization model using a mixed-integer linear programming approach to minimize the logistics cost. The logistics cost is a combination of the cost of transportation (Section 4.1.8a) and the cost per stop that the third-party provider incurs (Section 4.1.8c) while operating this model. This cost is largely defined by the transportation costs, which includes local delivery rounds, where the pickup vehicle makes a number of stops, and line-haul transport, where consolidated packages make a longer trip from the county centroids to the warehouse (Leg 1), directly from county centroids to the MRFs (direct) and warehouse to the MRF (leg 2).

This model considers c_{ij}, the logistics cost calculated based on $C_{logistics}$ in (7), which feeds into the optimization model formulation in (1). x_{ij} demonstrates the quantity of plastic collected, and z is the binary parameter which determines if the model should choose a direct path from the source (County) to the destination (MRFs) or it should choose a consolidation route through a warehouse of a third-party logistics provider or an e-commerce provider. The constraints are delineated from (2) through (6). The constraint in (2) is a binary parameter that decides whether a direct route is chosen, or a consolidation route is chosen. Constraint (3) describes the origin volume constraint, which can be explained as the volume that is considered from an origin point (county) cannot more than the post-consumer plastic generated at that point. Furthermore, (4) explains the capacity constraints on the intermediary point and the termination points of the route. Equation (5), explains the transshipment constraint which entails the number of pounds coming into a transshipment facility, leaves the facility in its entirety. Constraint (6) is a non-negativity constraint on the amount of material in flow from the source to the destination.

$$MIN(Z) = \sum_{i=1}^{n}\sum_{j=1}^{m} zc_{ij}x_{ij} + \sum_{i=1}^{n}\sum_{k=1}^{p}(1-z)c_{ik}x_{ik} + \sum_{k=1}^{p}\sum_{j=1}^{m}(1-z)c_{kj}x_{kj} \quad \dots (1)$$

Subject to:

$$z = \begin{cases} 0, & c_{ik} + c_{kj} < c_{ij} \\ 1, & c_{ik} + c_{kj} \geq c_{ij} \end{cases}, \forall\, i \in N_S, k \in N_I, j \in N_T \quad \dots (2)$$

$$\sum_{i} x_{ij} \leq Supply_i, \ \forall\, i \in N_S \quad \dots (3)$$

$$\sum_{j} x_{ij} \leq \gamma Capacity_j, \ \forall\, j \in \{N_I, N_T\}, \ 0 < \gamma < 1 \quad \dots (4)$$

$$\sum_{i} x_{ik} = \sum_{j} x_{kj}, \forall\, i \in N_S, k \in N_I, j \in N_T \quad \dots (5)$$

$$x_{ij} \geq 0 \quad \dots (6)$$

$$C_{logistics} = C_s\left[n + \frac{D}{\beta Q_{max}} + \frac{1}{2}\right] + C_d\left[2\left[\frac{D}{\beta Q_{max}} + \frac{1}{2}\right] d_{linehaul} + \frac{nk_{TSP}}{\sqrt{\delta}}\right] \quad \dots (7)$$

$$where,\ \delta = density = \frac{Demand}{Area} = \frac{D}{\pi r^2} \quad \dots (8)$$

β= capacity of the vehicle

This model presents the opportunity to several sensitivity parameters to evaluate different scenarios in terms of operations cost and overall profit of each scenario. These sensitivity scenarios help us to dynamically assess several factors. For example, a region can be categorized as rural and urban habitation based on the population ratio in terms of number of households per square mile. Similarly, other parameters aid the understanding of different scenarios based on geographic, social and economic likelihoods.

Sensitivity Parameters

n = number of households (collection points)

Q_{max} = Capacity of the transportation vehicle

r = radius of the area considered

D = Demand (based on company sales data, population ratio, and per-capita income of the county)

β = % capacity of the vehicle used

This formulation enables us to perform the optimization to understand, based on the location of the warehouses and MRFs, which leg of transport is the most cost effective. After the formulation of this model we to perform cost analysis for the company enabling the process of take-back.

4.5 Cost Analysis

After devising the model using a network design approach and coming up with the transportation routes, we now calculate the profit margin for the company facilitating this take-back process. In this we take the perspective of the CPG company and assume that the CPG company is facilitating this take-back process. However, this analysis will hold good for any entity that facilitates this take-back process, such as a logistics service provider or recycling company who will plan to sell the recycled plastic to plastic manufacturers.

To perform this cost analysis, we consider the following flow of actual post-consumer plastic from the consumer to the CPG company through various processes.

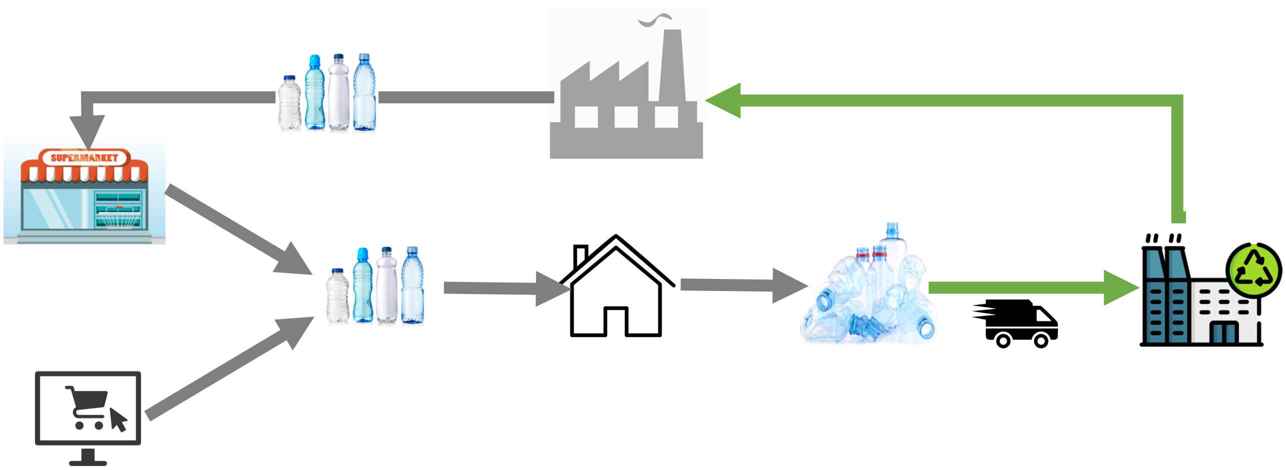


Figure 11. Flow of the post-consumer plastic based on model developed in this research

To perform the cost analysis, we have come up with a generic equation. The equation below represents a mathematical formulation, which takes into consideration the purchase price of virgin and recycled plastic. The formulation suggests a parameter **a** that varies between 0 and 1 and determines the component structure of the products of the CPG company. It estimates the price that the CPG company will not have to pay if they undertake this process of facilitating the take-back of plastics and thereby facilitating recycling, and then collects and uses the recycled plastic pellets to manufacture future plastic packaging.

In this equation, we also consider a total cost, which is composed of the following costs, as covered in Sections 4.1.8 and 4.4: (1) Recycling cost, (2) Logistics Cost, (3) Cost of Storage, (4) Cost of Sorting (usually included in the recycling cost), and (5) Parameterized cost of incentives.

$$\alpha P_{virgin} + (1 - \alpha) P_{recycled} - Total\ Cost = Margin - \hat{E}(C_{env})$$

where,

$0 < \alpha < 1,$

$$Total\ Cost = C_{rec} + C_{logistics} + C_{storage} + C_{sorting} + C_{incentives}$$

where,

P_{virgin} = Purchase Price of virgin plastic

C_{env} = Estimated environmental cost

$P_{recycled}$ = Price of Recycled Plastic

C_{rec} = Recycling cost

$C_{logistics}$ = Total Logistics Cost

$C_{sorting}$ = Sorting Cost

$C_{incentives}$ = Incentives Costs

$C_{storage}$ = Storage Cost

After conducting the cost analysis and applying the formula to the modeled data, we then conduct a scenario-based sensitivity analysis.

4.6 Scenario-Based Sensitivity Analysis

After completing the cost analysis, we perform the sensitivity analysis based on different sensitivity parameters, as mentioned in Section 4.4. In this sensitivity analysis we change the different parameters to understand the impact on the profit margin of the entity facilitating the take-back process. For this research we do the sensitivity analysis from the perspective of the CPG company that is facilitating the process.

To conduct the sensitivity analysis, we use the results from the cost analysis for all the counties in the New England states, and plot them in four different graphs showing each of the following relationships: (1) margin across all the counties; (2) different types of costs across all the counties; (3) specifically logistics cost across the counties; and (4) emission cost vs. margin across all the counties.

Based on this analysis we can understand which scenarios work well from an economic perspective and how the choice of distance and vehicle affect the greenhouse gases emitted from the transportation required by this process. The effect of emissions is further analyzed based on the cost to the company using a carbon price ($ per ton-CO_2). The results from the sensitivity analysis is detailed in Section 5.4.

In our analysis, however, we do not subtract the emissions cost from the margin. We show it separately as this can be further acted upon using various other measures, such as carbon offsets and the cost of investment in an electric fleet.

After conducting the sensitivity analysis, we are poised to make recommendations to the company facilitating this take-back process.

4.7 Recommendations

After performing the sensitivity analysis, we make recommendations to the entity sponsoring this take-back process based on what parameters to choose to maximize economic benefit while minimizing emissions and ensuring greater plastic collection. The plastic collection, however, is dependent on customer responsibility, which can be further assessed using "pay or punish" model. A deeper understanding of incentives can help in assessing if there is a relationship between collection percentage and stakeholder incentives.

We used this methodology (Section 4) to conduct our studies and calculations and reached the results discussed in the next section.

5. Results

After discussing the methodology for this research, we now discuss the results that were obtained by conducting the analysis on the data collected. These results and sensitivity analysis present the outcome of running the optimization-based network design model and the cost analysis defined in the chapter 4, Methodology.

These results are broken down into initial data clustering based on product types and contents, and geographic distribution of locations in terms of counties, Amazon warehouses, and material recovery facilities (MRFs). The results also demonstrate optimized route distances, the cost structures and the profit margin as described in the Methodology section.

5.1 Initial Data Analysis

Upon executing the methodology as mentioned in Chapter 4, we find several interesting insights from the initial data analysis as described in Section 4.3. We first found the weights of different types of plastics as described in Table 5.1.1.

Table 5.1.1 Overall weight of plastics by annual sales in CPG Industry

Type of Plastic	Metric Tons
HD-POLYETHYLENES	9820.39
LD-POLYETHYLENES	204.81
POLYESTERS	220504.00
POLYPROPYLENES	304792.00

We see that polyesters (the majority of which is PET) and polypropylenes dominate the post-consumer plastic space.

Next, we understand the relative per capita income among the New England states and see that Connecticut has the highest relative per-capita income, followed by Massachusetts, and then by New Hampshire, Rhode Island, Vermont and Maine. Table 5.1.2 demonstrates this.

Table 5.1.2. Per capita income by New England states

State	Per-capita Income	Per-capita Income density
Maine	$ 48,905.00	0.898
Vermont	$ 54,173.00	0.995
Rhode Island	$ 54,850.00	1.007
New Hampshire	$ 61,294.00	1.126
Massachusetts	$ 71,683.00	1.317
Connecticut	$ 76,456.00	1.404

Similarly, we see that the population ratio of Massachusetts is the highest followed by Connecticut and then by New Hampshire, Maine, Rhode Island and Vermont. This is demonstrated in Table 5.1.3

Table 5.1.3. Population ratio of New England states

State	Population ratio
Vermont	0.19
Rhode Island	0.32
Maine	0.41
New Hampshire	0.41
Connecticut	1.09
Massachusetts	2.11

After finding the population ratio and the relative per-capita income density, we can then calculate the normalizing parameter which, when multiplied with the sales values, can give a near estimate of the weight of products sold in specific counties. A snapshot of the data is provided in Table 5.1.4, where we show the state, the counties, and the normalized weights of the plastics of different types. The full table can be seen in Appendix A.

Table 5.1.4 Detailed distribution of plastic sold by plastic type by county in New England (in Metric Tons)					
States and Counties	**Total Plastic**	**PET**	**PP**	**HDPE**	**LDPE**
Connecticut	10519.91	4333.25	5989.65	192.99	4.025
Fairfield County	4384.79	1806.13	2496.54	80.44	1.68
Hartford County	2229.71	918.44	1269.51	40.90	0.85
Litchfield County	453.05	186.62	257.95	8.31	0.17
Middlesex County	430.22	177.21	244.95	7.89	0.16
New Haven County	1871.09	770.72	1065.33	34.32	0.72
New London County	608.89	250.81	346.68	11.17	0.23
Tolland County	329.07	135.55	187.36	6.04	0.13
Windham County	213.02	87.75	121.29	3.91	0.08
Maine	2520.87	1038.37	1435.29	46.25	0.96
Androscoggin County	172.21	70.93	98.05	3.16	0.066
Aroostook County	106.58	43.90	60.68	1.96	0.04
Cumberland County	706.90	291.18	402.48	12.97	0.27
Franklin County	44.39	18.28	25.27	0.81	0.02
Hancock County	108.18	44.56	61.60	1.98	0.04

After data preparation we run the network optimization model, and the results of which are mentioned in the next section.

5.2 Optimized Routes and Corresponding Distances

After the initial data analysis and data preparation we ran the optimization to get the routes from every county to the MRF. This process was executed in detail as described in Section 4.4.

To run the model, we assumed that the facilities in the model, e.g., the Amazon warehouses and the MRFs, have infinite capacity. Thus, the facilities selected by the model to form a route were primarily chosen based on the minimum distance as the transportation cost and the cost to stop (as described in Section 4.1.8) were negligible for the local distances within the service radius in the county.

Furthermore, we saw that all the distances selected are direct distances (shortest feasible distance) due to the distance minimization (as described in Section 4.1.8). To normalize this, we break down the consolidation distance in Leg 1 and Leg 2 and capture the consolidation route if the Leg 2 distance is less than the direct distance. This logic signifies that if the CPG company were to employ a 3PL provider, it will only do so if the Leg 2 distance is shorter than the direct distance. In this case the transportation cost incurred in the Leg 1 distance is an additional cost the CPG company is willing to incur due to the benefits of consolidation, which results in overall cost reduction.

In Table 5.2.1 we show the selected distances for the counties, some of which are direct and the remaining are through a consolidation network. The Table 5.2.1 shows county IDs, MRF IDs, and Amazon Warehouse IDs, which are identifiers to represent a county, an MRF and an Amazon warehouse, respectively, and this has been utilized for easy of multi-functional data analysis. The full description of these Ids, can be found in Appendices B, C and D. Table 5.2.1 shows a snapshot of the data. The entire table can be seen in Appendix F.

Table 5.2.1 Distances in Miles between County and MRF (on left) and Distances between County and MRF Through Amazon Warehouse (right)

CTY_ID	MRF_ID	Miles	Final for Cost	Total Distance (including Leg 1)	CTY_ID	AMZ_ID	MRF_ID	Miles
CTY_CT_1	MRF_CT_4	12.14	12.14	12.14	CTY_CT_1	AMZ_4	MRF_CT_3	59.21
CTY_CT_2	MRF_CT_8	14.63	13.19	25.04	CTY_CT_2	AMZ_5	MRF_CT_7	25.04
CTY_CT_3	MRF_CT_4	34.15	13.91	57.59	CTY_CT_3	AMZ_3	MRF_CT_5	57.59
CTY_CT_4	MRF_CT_5	24.15	13.91	35.21	CTY_CT_4	AMZ_3	MRF_CT_5	35.21
CTY_CT_5	MRF_CT_3	22.08	21.26	30.95	CTY_CT_5	AMZ_4	MRF_CT_3	30.95
CTY_CT_6	MRF_CT_6	20.02	13.19	64.56	CTY_CT_6	AMZ_5	MRF_CT_7	64.56
CTY_CT_7	MRF_CT_6	12.45	12.45	12.45	CTY_CT_7	AMZ_5	MRF_CT_7	37.09
CTY_CT_8	MRF_CT_6	16.26	13.19	58.65	CTY_CT_8	AMZ_5	MRF_CT_7	58.65
CTY_MA_1	MRF_MA_1	33.35	27.58	90.65	CTY_MA_1	AMZ_2	MRF_MA_2	90.65
CTY_MA_10	MRF_MA_9	15.41	1.63	32.14	CTY_MA_10	AMZ_6	MRF_MA_4	32.14

This table clearly shows the route choices made and the final distances to be used in the total systemic cost calculation, results of which we discuss in Section 5.3.

5.3 Margin and Cost Analysis based on Demand

After finding the optimal distances from every county to the closest MRF, we further calculated the different components of the cost: the transportation cost, the stop cost, the overall logistics cost, recycling cost, and the incentive cost (with the value of incentives as zero dollars to begin with). We also calculate the price based on the weight of the post-consumer plastic for every plastic class. This is important to understand what the CPG company would have spent to manufacture the product packaging using virgin plastic. This finally brings us to calculating the profit margin, which is calculated by subtracting the different costs from the price of the virgin plastic.

Table 5.3.1 shows a snapshot of the whole calculation that was performed. The full table can be found in Appendix E.

Table 5.3.1 Aggregated cost and price calculation for all the counties by plastic classes (aggregation not shown in this table)

									Costs				Price	Profit		
CTY_ID	Total (miles)	Plastic Waste (Lb)	Local Distance (miles) Household (n =50) radius = 5	Linehaul (miles) MaxLoad=3500 Capacity=0.2	Total Distance (miles)	Transport Cost	Stopage Household (n =50) MaxLoad=3500 Capacity=0.2	Stop Cost	Logistics Cost ($)	Recycling Cost (includes sorting) ($)	Storage Cost ($)	Incentive Cost ($)	Total P_virgin ($)	Margin ($)	Emissions g-CO2	Emission Cost ($)
CTY_CT_1	12.14	9666801.23	0.17	335355.94	335356.11	$ 798,147.55	13860.22	$138.60	$ 798,286.16	$ 580,008.07	$ -	$ 6,000.00	$ 5,254,290.00	$3,869,995.77	1622887724	43817.97
CTY_CT_2	25.04	4915658.42	0.24	351696.68	351696.92	$ 837,038.67	7072.87	$70.73	$ 837,109.40	$ 294,939.51	$ 56,284.55	$ 6,000.00	$ 2,671,855.38	$1,477,521.93	3509934137	94768.22
CTY_CT_3	57.59	998804.07	0.53	164392.76	164393.29	$ 391,256.03	1477.36	$14.77	$ 391,270.80	$ 59,928.24	$ 11,436.36	$ 6,000.00	$ 542,889.64	$ 74,254.23	3773193254	101876.22
CTY_CT_4	35.21	948481.56	0.55	95444.00	95444.55	$ 227,158.02	1405.47	$14.05	$ 227,172.07	$ 56,908.89	$ 10,860.16	$ 6,000.00	$ 515,537.36	$ 214,596.23	1339323127	36161.72
CTY_CT_5	30.95	4125042.18	0.26	364779.01	364779.27	$ 868,174.67	5943.42	$59.43	$ 868,234.10	$ 247,502.53	$ 47,231.95	$ 6,000.00	$ 2,242,124.08	$1,073,155.50	4499554359	121487.97
CTY_CT_6	64.56	1342373.65	0.46	247667.15	247667.61	$ 589,448.90	1968.18	$19.68	$ 589,468.59	$ 80,542.42	$ 15,370.25	$ 6,000.00	$ 729,633.34	$ 38,252.08	6372732973	172063.79
CTY_CT_7	12.45	725469.31	0.62	25828.30	25828.93	$ 61,472.84	1086.88	$10.87	$ 61,483.71	$ 43,528.16	$ -	$ 6,000.00	$ 394,321.36	$ 283,309.48	128217831.6	3461.88
CTY_CT_8	58.65	469635.77	0.78	78756.98	78757.75	$ 187,443.45	721.41	$7.21	$ 187,450.66	$ 28,178.15	$ 5,377.35	$ 6,000.00	$ 255,265.67	$ 28,259.51	1841078799	49709.13
CTY_MA_1	90.65	1354581.64	0.46	350912.67	350913.13	$ 835,173.25	1985.62	$19.86	$ 835,193.11	$ 81,274.90	$ 15,510.03	$ 6,000.00	$ 736,268.87	$ (201,709.17)	12678154382	342310.17
CTY_MA_10	32.14	11488205.98	0.16	1054970.91	1054971.07	$ 2,510,831.14	16462.22	$164.62	$2,510,995.76	$ 689,292.36	$131,540.57	$ 6,000.00	$ 6,244,295.75	$2,906,467.06	13514199858	364883.40
CTY_MA_11	124.62	119343.16	1.54	42617.71	42619.25	$ 101,433.81	220.99	$2.21	$ 101,436.02	$ 7,160.59	$ 1,366.49	$ 6,000.00	$ 64,867.74	$ (51,095.35)	2116904647	57156.43
CTY_MA_12	8.11	5527027.49	0.23	128089.17	128089.39	$ 304,852.75	7946.25	$79.46	$ 304,932.22	$ 331,621.65	$ 63,284.76	$ 6,000.00	$ 3,004,158.73	$2,298,320.10	414077078.7	11180.08
CTY_MA_13	9.91	2969754.92	0.31	84082.67	84082.98	$ 200,117.49	4293.01	$42.93	$ 200,160.42	$ 178,185.30	$ -	$ 6,000.00	$ 1,614,179.62	$1,229,833.91	332060735.9	8965.64
CTY_MA_14	20.41	5562250.45	0.23	324371.95	324372.18	$ 772,005.78	7996.57	$79.97	$ 772,085.74	$ 333,735.03	$ 63,688.06	$ 6,000.00	$ 3,023,303.80	$1,847,794.97	2638662029	71243.87
CTY_MA_15	23.80	4021218.59	0.27	273435.26	273435.52	$ 650,776.54	5795.10	$57.95	$ 650,834.49	$ 241,273.12	$ -	$ 6,000.00	$ 2,185,691.85	$1,287,584.24	2593514694	70024.90
CTY_MA_2	79.32	606171.52	0.68	137447.35	137448.03	$ 327,126.31	916.46	$9.16	$ 327,135.48	$ 36,370.29	$ 6,940.70	$ 6,000.00	$ 329,478.27	$ (46,968.19)	4345136415	117318.68
CTY_MA_3	38.00	2590347.12	0.33	281279.87	281280.20	$ 669,446.87	3751.00	$37.51	$ 669,484.38	$ 155,420.83	$ 29,659.61	$ 6,000.00	$ 1,407,956.43	$ 547,391.61	4260258173	115026.97
CTY_MA_3	106.60	137990.03	1.43	42135.86	42137.29	$ 100,286.76	247.63	$2.48	$ 100,289.24	$ 8,279.40	$ 1,579.99	$ 6,000.00	$ 75,003.06	$ (41,145.58)	1790380891	48340.28
CTY_MA_4	18.18	4531743.61	0.25	235410.83	235411.08	$ 560,278.38	6524.42	$65.24	$ 560,343.62	$ 271,904.62	$ -	$ 6,000.00	$ 2,463,182.45	$1,624,934.21	1705804383	46056.72
CTY_MA_5	67.30	329512.04	0.93	63429.00	63429.92	$ 150,963.22	521.23	$5.21	$ 150,968.43	$ 19,770.72	$ 3,772.93	$ 6,000.00	$ 179,102.87	$ (1,409.21)	1701470538	45939.70

This analysis shows the different costs and the margins for each individual county based on the calculated price of virgin plastic and the summation of all the costs included here. Furthermore, we also estimate the emissions based on the number of trips and weight carried per trip and through different vehicle type. We then calculate the emissions cost based on global average price of mandated carbon taxes (The World Bank, 2020). We now perform a sensitivity analysis to understand the aggregated behavior of this system.

5.4 Scenario-based Sensitivity Analysis

As described in the methodology, we show the results from the sensitivity analysis performed by varying the various sensitivity parameters in Table 5.4.0:

Table 5.4.0: Parameters for Sensitivity Analysis	
Transport Cost ($ / mile)	Number of Households (units)
Storage cost ($)	Capacity of the vehicle (lbs.)
Cost of recycling ($ / ton)	Percentage of capacity used (%)
Incentive Cost ($ / Household / Month)	Distance negotiated (Yes / No)
Radius of coverage (miles)	Type of vehicle (Type 1 or Type 2)

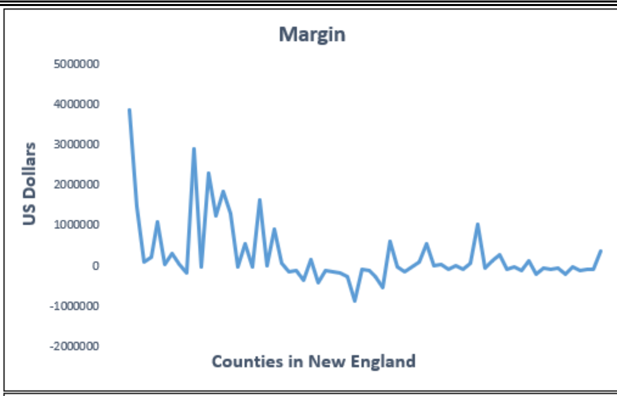
In all the below scenarios we also consider that the collection is 100 percent which means that the amount of plastic that is sold (in tons) is collected from the consumer after use through this take-back process.

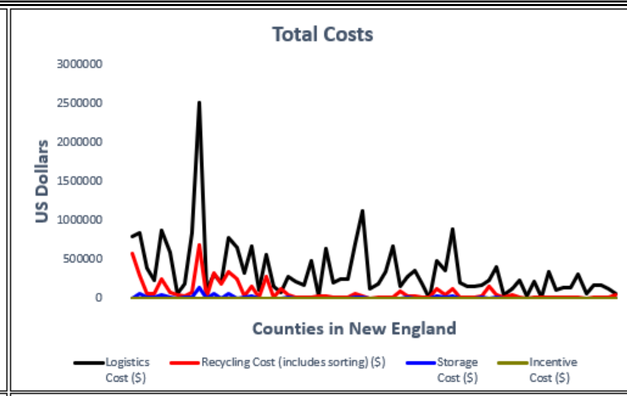
While conducting the sensitivity analysis we first consider a base case, as described in Table 5.4.1 and other different cases as described in Tables 5.4.2, 5.4.3, 5.4.4, 5.4.5, 5.4.6.1, 5.4.6.2, 5.4.7.1, 5.4.7.2, 5.4.8.1, and 5.4.9. The base case scenario is decided based on the generic use cases and the most commonly used scenarios. Table 5.4.1 and others as mentioned before is composed of parameters which are described in Table 5.4.0. The afore mentioned Tables also consists of Results in terms of Total Cost incurred, and Total Margin, which suggests a positive or a negative margin, and Emissions Cost, which is incurred based on the vehicle choices while conducting the sensitivity analysis. Furthermore, the plots in the Table 5.4.1 represent: (1) Margin in US dollars over all the counties in New England; (2) Cost in US dollars over all the counties in New England; (3) Emissions Cost over all the counties in New England; and (4) Logistics Cost, which is a specific component of the total cost. These plots show vividly how the different choice of parameters changes the nature of the plots.

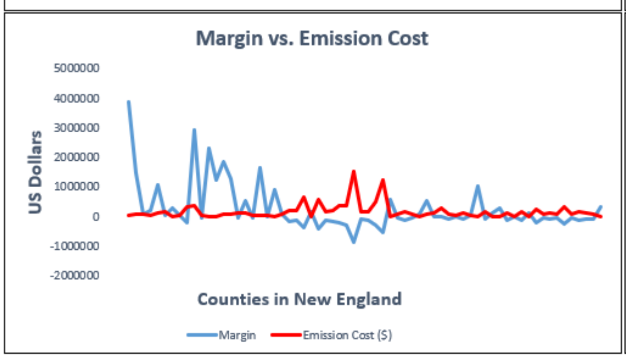
5.4.1 Base Case Scenario

Table 5.4.1 shows the base case scenario results for sensitivity analysis.

Table 5.4.1: Base case scenario for sensitivity analysis	
Transport Cost ($/mile) - $2.38 /mile	Number of Households (units) - 50
Storage cost ($) - $0.69	Capacity of the vehicle - 3,500 lbs.
Cost of recycling ($/US ton) - $120	Percentage of capacity used - 20%
Incentive Cost ($ / Household / Month) - $0	Distance negotiated - No
Radius of coverage – 5 miles	Type of vehicle (for emission cost) – Type 1
Results	
Total Cost	$28,877,785.74
Total Margin	$17,565,058.04
Total Emissions Cost	$11,286,808.44
Plots	



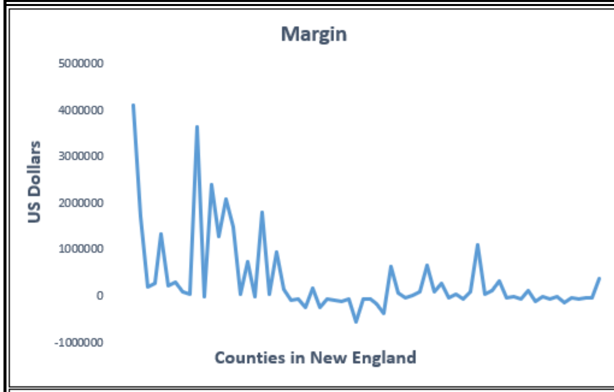


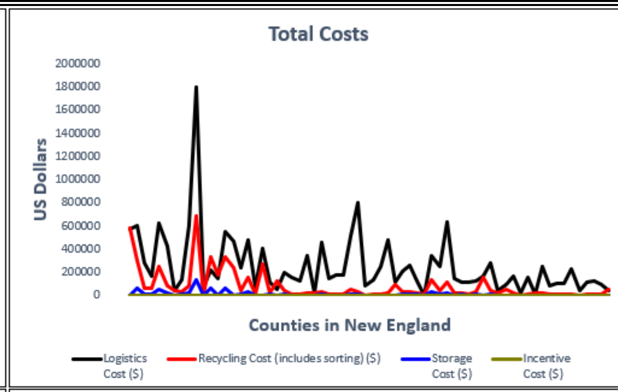


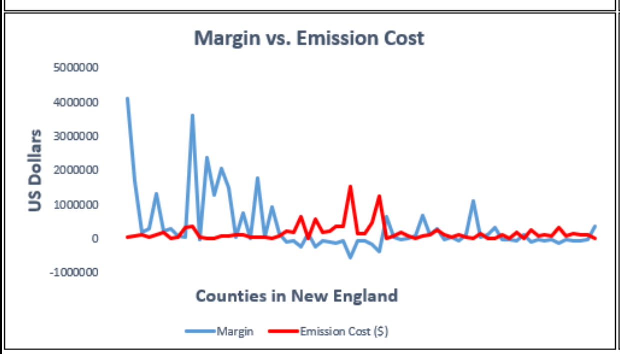
5.4.2 Impact of Transport Cost

In Table 5.4.2, we consider a lower transportation cost of $ 1.7 per mile, and the results are as expected. The margin is higher, and both the overall cost and logistics cost are lower. This is an important scenario, as we show that if the CPG company can negotiate the transportation cost with the logistics provider, this venture becomes even more profitable.

Table 5.4.2: Lower transportation cost scenario for sensitivity analysis	
Parameters	
Transport Cost ($/mile) - $1.70 /mile	Number of Households (units) - 50
Storage cost ($) - $0.69	Capacity of the vehicle - 3,500 lbs.
Cost of recycling ($/US ton) - $120	Percentage of capacity used - 20%
Incentive Cost ($ / Household / Month) - $0	Distance negotiated - No
Radius of coverage – 5 miles	Type of vehicle (for emission cost) – Type 1
Results	
Total Cost	$22,270,387.39
Total Margin	$24,172,456.39
Total Emissions Cost	$11,286,808.44
Plots	



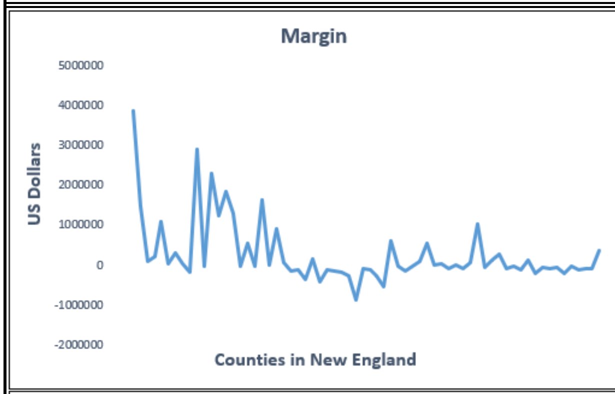


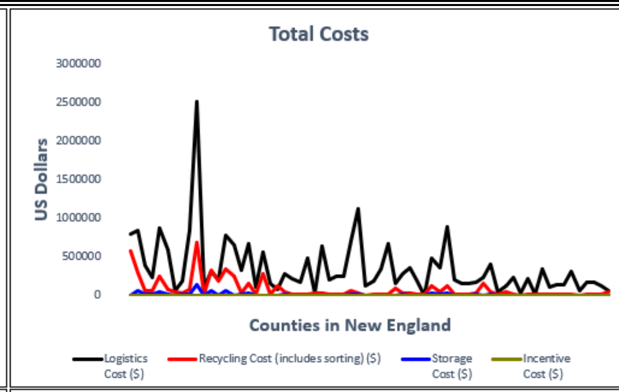


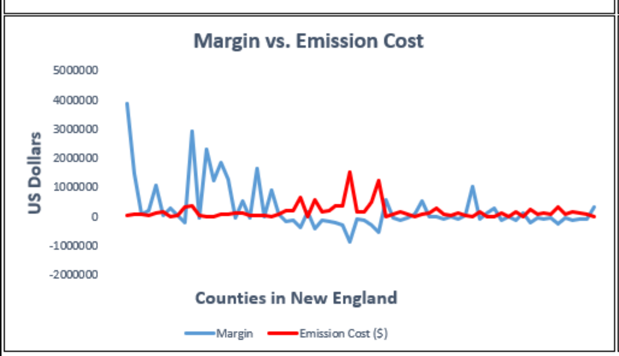
5.4.3 Impact of Service Radius and Number of Households Per Trip

In Table 5.4.3, we deviate from the base case in terms of the service radius (increase to 20 miles) and the number of pickups per trip (increase to 100). Increasing the coverage increases the number of miles traveled in the local distance, thus increasing the transport cost. But this effect is not significant on the overall cost and profit margin.

Table 5.4.3: Larger service area within a county (larger radius, more pickups)	
Parameters	
Transport Cost ($/mile) - $2.38 /mile	**Number of Households (units) - 100**
Storage cost ($) - $0.69	Capacity of the vehicle - 3,500 lbs.
Cost of recycling ($/US ton) - $120	Percentage of capacity used - 20%
Incentive Cost ($ / Household / Month) - $0	Distance negotiated - No
Radius of coverage – 20 miles	Type of vehicle (for emission cost) – Type 1
Results	
Total Cost	$28,878,865.92
Total Margin	$17,563,977.86
Total Emissions Cost	$11,287,545.90
Plots	



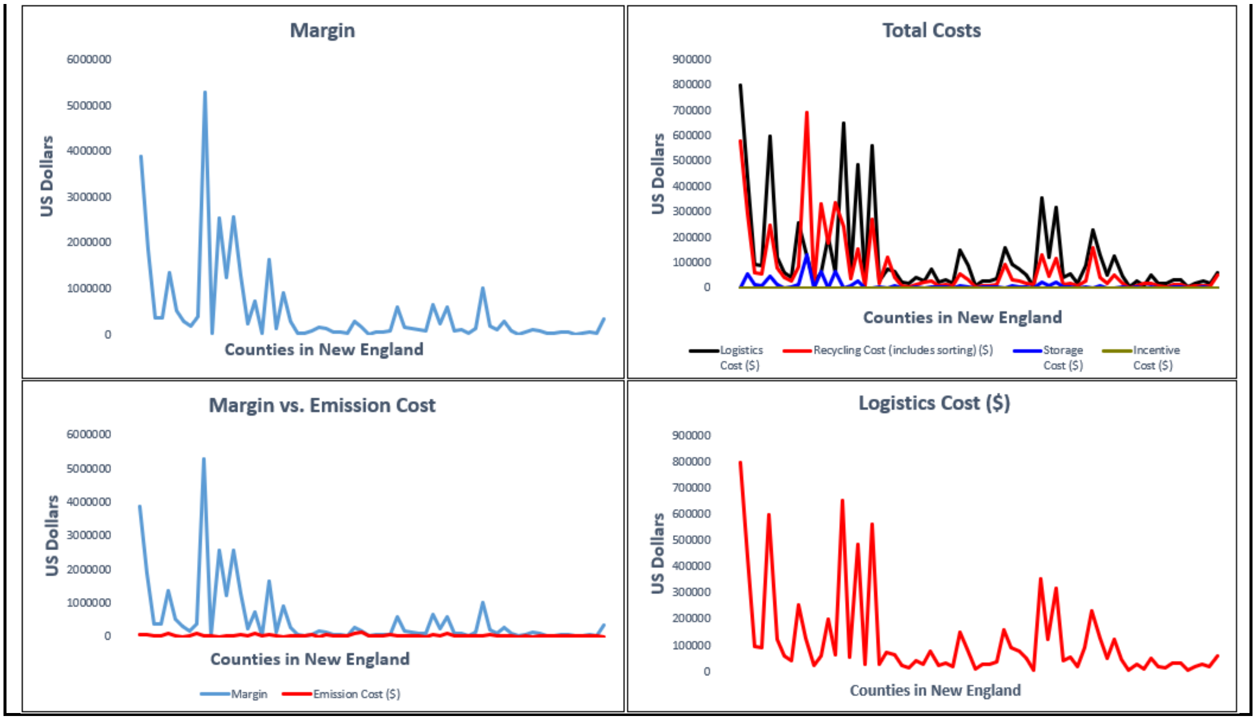




5.4.4 Partnering to Share Logistics Cost

Here we consider that we decide on a consolidation-based logistics strategy, and the CPG company partners with the 3PL player and pays only for the second leg of the transportation. We consider this scenario in the assumption, that the 3PL provider would make deliveries anyway and must come back to the warehouse location, and in the process would just pick up the post-consumer plastic. This shows an expected increase in the margin for the company because of lower logistics cost. This also reduces the emissions cost as borne by the sponsoring entity, because we only consider one leg of the journey and hold the assumption that the Leg 1 of the journey would be completed anyway by the 3PL provider.

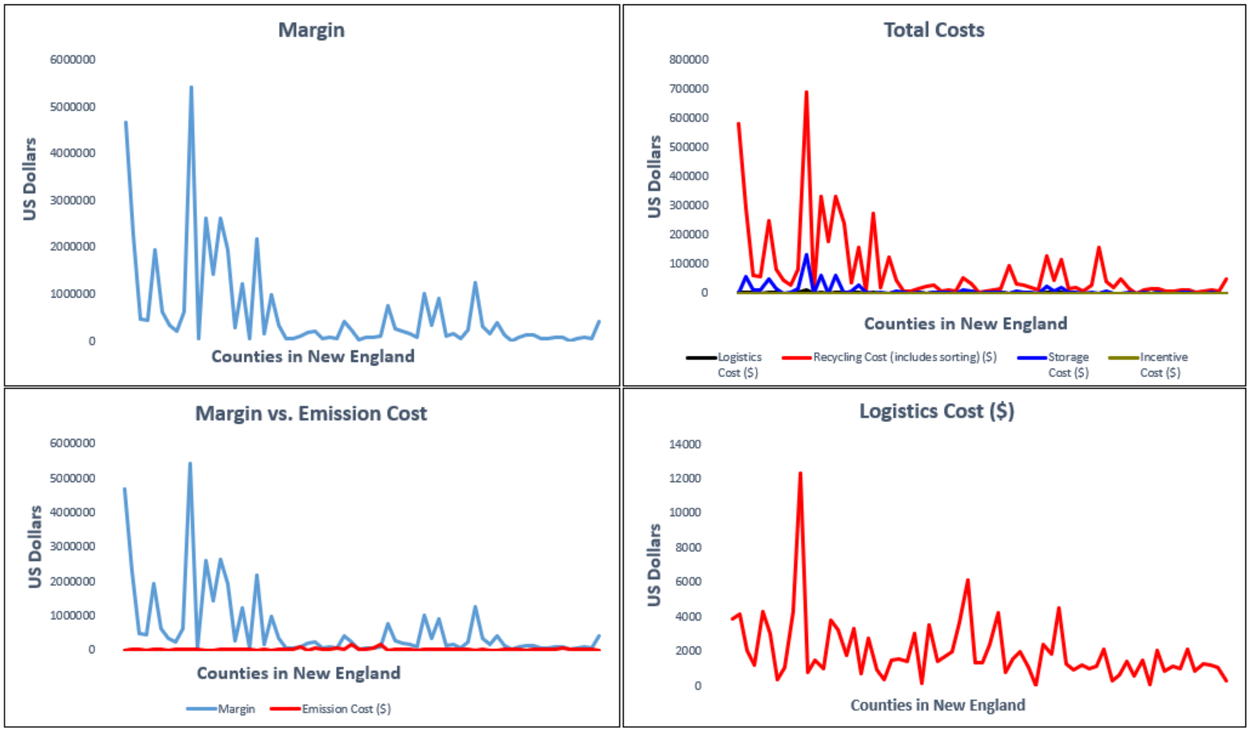
Table 5.4.4: Partnering to share logistics cost	
Parameters	
Transport Cost ($/mile) - $2.38 /mile	Number of Households (units) - 50
Storage cost ($) - $0.69	Capacity of the vehicle - 3,500 lbs.
Cost of recycling ($/US ton) - $120	Percentage of capacity used - 20%
Incentive Cost ($ / Household / Month) - $0	**Distance negotiated - Yes**
Radius of coverage – 5 miles	Type of vehicle (for emission cost) – Type 1
Results	
Total Cost	$13,529,765.42
Total Margin	$32,913,078.36
Total Emissions Cost	$1,927,298.44
Plots	



5.4.5 Impact of The Capacity of the Vehicle Used

Here we consider the impact of the capacity of the vehicle. We deviate from the base case scenario by changing the capacity of the vehicle to 720,000 lbs. and the emission type to Type 2. We see that the margin drastically improves and the effect on emissions cost also lowers. This behavior is attributed to the reduction in the number of trips to collect all the post-consumer plastic.

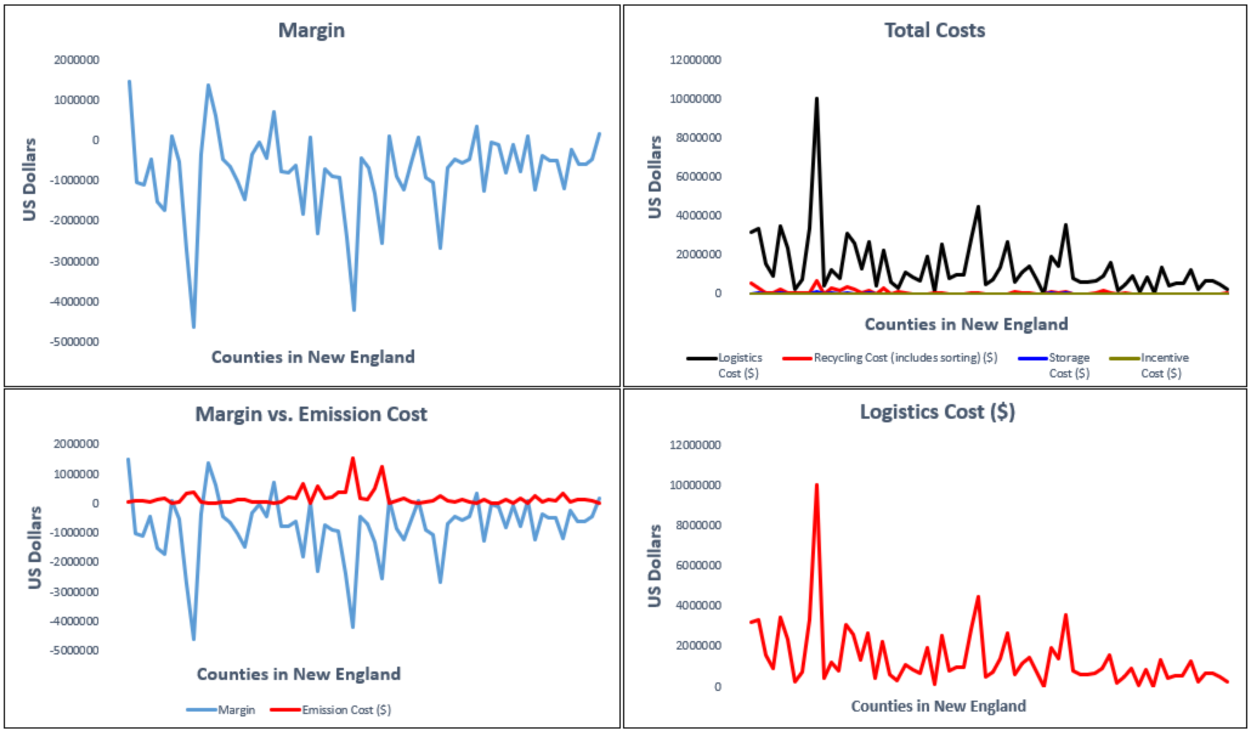
Table 5.4.5: Impact of capacity of vehicle	
Parameters	
Transport Cost ($/mile) - $2.38 /mile	Number of Households (units) - 50
Storage cost ($) - $0.69	**Capacity of the vehicle - 720,000 lbs.**
Cost of recycling ($/US ton) - $120	Percentage of capacity used - 20%
Incentive Cost ($ / Household / Month) - $0	Distance negotiated - No
Radius of coverage – 5 miles	**Type of vehicle (for emission cost) – Type 2**
Results	
Total Cost	$5,881,016.13
Total Margin	$40,561,827.65
Total Emissions Cost	$1,368,050.34
Plots	



5.4.6 Impact of Percentage of the Vehicle Capacity Used in Type 1 Vehicle

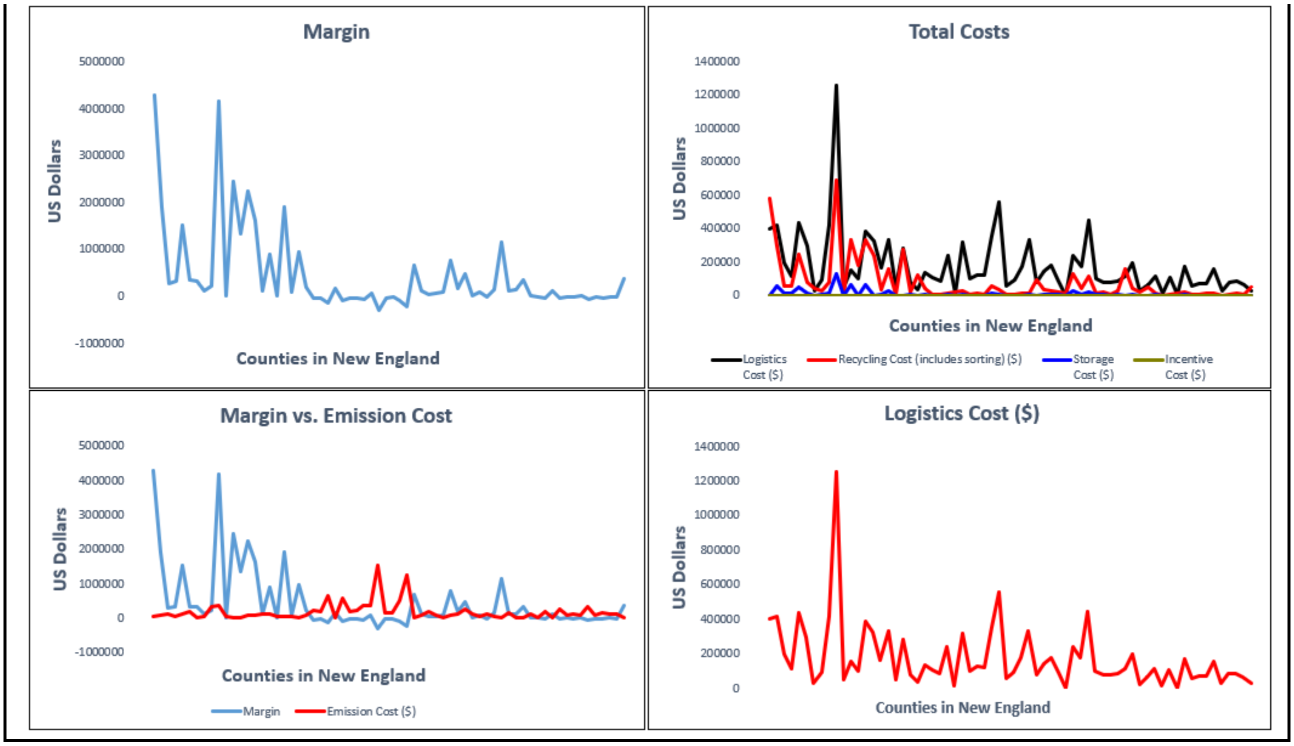
In this scenario we consider 5% of the capacity used for the standard delivery van instead of 20% as in the base case scenario. This results in a loss for the CPG company, as there are multiple trips required to pick up the post-consumer plastic.

Table 5.4.6.1: Impact of percentage of the vehicle capacity used in Type 1 vehicle	
Parameters	
Transport Cost ($/mile) - $1.70 /mile	Number of Households (units) - 50
Storage cost ($) - $0.69	Capacity of the vehicle - 3,500 lbs.
Cost of recycling ($/US ton) - $120	**Percentage of capacity used - 5%**
Incentive Cost ($ / Household / Month) - $0	Distance negotiated - No
Radius of coverage – 5 miles	Type of vehicle (for emission cost) – Type 1
Results	
Total Cost	$98,205,102.36
Total Margin	$(51,762,258.58)
Total Emissions Cost	$11,274,605.89
Plots	



In the following scenario we increase the capacity to 40% to see how the margin and the emissions cost change. It is important to understand that increasing the capacity of the vehicle reduces the number of trips required thereby reducing the overall transportation cost and thus improving the margin. It also reduces the emissions and thereby the emissions cost.

Table 5.4.6.2: Impact of percentage of the vehicle capacity used in Type 1 vehicle	
Parameters	
Transport Cost ($/mile) - $2.38 /mile	Number of Households (units) - 50
Storage cost ($) - $0.69	Capacity of the vehicle – 3,500 lbs.
Cost of recycling ($/US ton) - $120	**Percentage of capacity used - 40%**
Incentive Cost ($ / Household / Month) - $0	Distance negotiated - No
Radius of coverage – 5 miles	Type of vehicle (for emission cost) – Type 1
Results	
Total Cost	$17,323,232.97
Total Margin	$29,119,610.81
Total Emissions Cost	$11,303,078.51
Plots	



5.4.7 Impact of the Percentage of Vehicle Capacity Used on Type 2 Vehicle

We now conduct a sensitivity analysis by changing the percentage of capacity used for the Type 2 vehicle (capacity ~ 720,000 lbs.). We use two scenarios for the percentage used as 5% and 40%. The results for 5% capacity used can be seen in Table 5.4.7.1 and the results for 40% capacity used can be seen in Table 5.4.7.2.

Table 5.4.7.1: Impact of percentage of the vehicle capacity used in Type 2 vehicle	
Parameters	
Transport Cost ($/mile) - $2.38 /mile	Number of Households (units) - 50
Storage cost ($) - $0.69	**Capacity of the vehicle – 720,000 lbs.**
Cost of recycling ($/US ton) - $120	**Percentage of capacity used - 5%**
Incentive Cost ($ / Household / Month) - $0	Distance negotiated - No
Radius of coverage – 5 miles	**Type of vehicle (for emission cost) – Type 2**
Results	
Total Cost	$ 6,218,023.92
Total Margin	$ 40,224,819.86
Total Emissions Cost	$ 1,133,117.68
Plots	

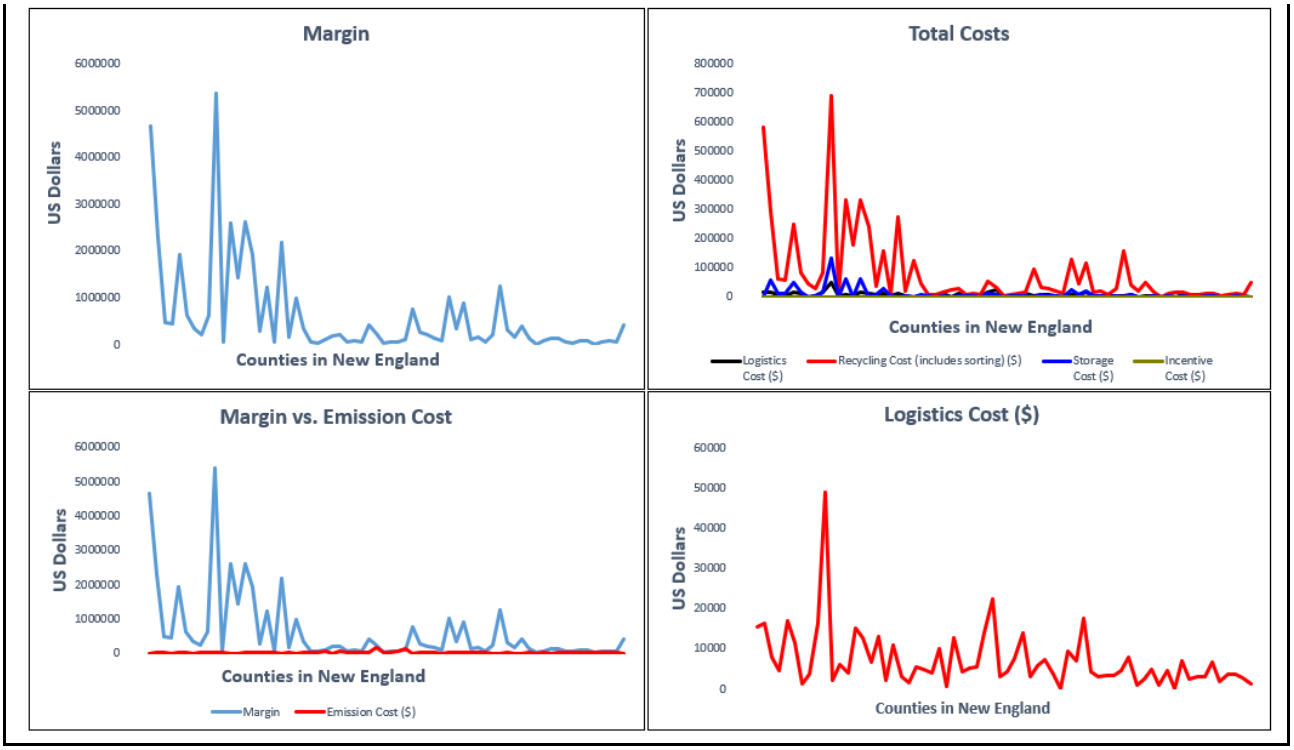
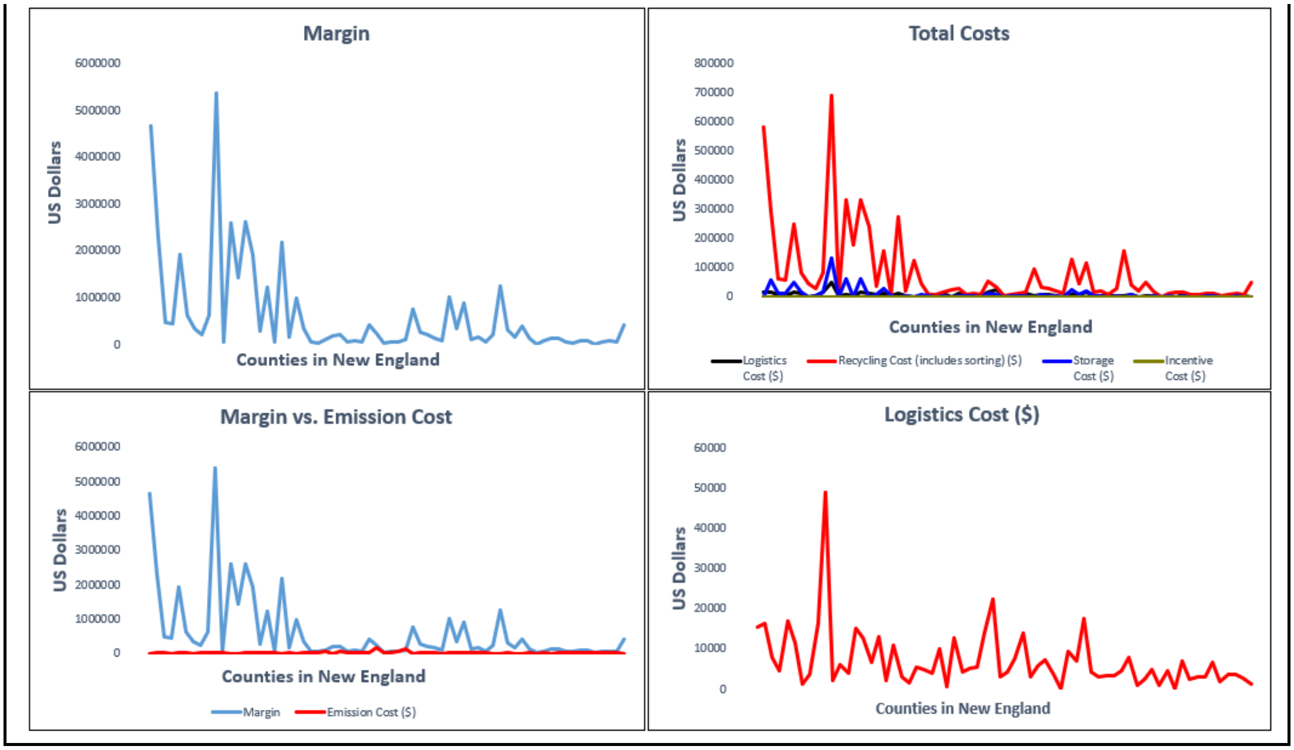


Table 5.4.7.2: Impact of percentage of the vehicle capacity used in Type 2 vehicle	
Parameters	
Transport Cost ($/mile) - $2.38 /mile	Number of Households (units) - 50
Storage cost ($) - $0.69	**Capacity of the vehicle - 720,000 lbs.**
Cost of recycling ($/US ton) - $120	**Percentage of capacity used - 40%**
Incentive Cost ($ / Household / Month) - $0	Distance negotiated - No
Radius of coverage – 5 miles	**Type of vehicle (for emission cost) – Type 2**
Results	
Total Cost	$ 5,824,848.17
Total Margin	$ 40,617,995.61
Total Emissions Cost	$ 1,681,293.88
Plots	



Based on the results in Tables 5.4.7.1 and 5.4.7.2 we can see that there is not much of a difference in the cost and margin in these two scenarios. The difference is primarily attributed to the local distance covered during the pick-up and not the line-haul distance. This suggests that when using both 5% and 40% of the capacity for a large vehicle the number of trips is approximately the same for constant demand, which in this case is the consumed weight of the post-consumer plastic. This compared with Section 5.4.6, where we do the analysis based on the Type 1 vehicle, is very different because for the smaller vehicle the number of trips is greatly increased.

5.4.8 Impact on Greenhouse Gas Emissions

In this scenario analysis we focus on the greenhouse gas emissions for the two primarily types of vehicles we use in this model, viz. Type 1 and Type 2. These two vehicles vary in capacity and in their carbon intensity (CO_2e / ton-mile). Carbon intensity for Type 1 is 780 and for Type 2 it is 73. We calculate the emissions based on the GLEC framework (Greene & Lewis, 2019)

Table 5.4.8.1: Emissions in Type 1 vehicle	
Parameters	
Transport Cost ($/mile) - $2.38 /mile	Number of Households (units) - 50
Storage cost ($) - $0.69	**Capacity of the vehicle - 3,500 lbs.**
Cost of recycling ($/US ton) - $120	Percentage of capacity used - 20%
Incentive Cost ($ / Household / Month) - $0	Distance negotiated - No
Radius of coverage – 5 miles	**Type of vehicle (for emission cost) – Type 1**
Results	
Total Cost	$28,877,785.74
Total Margin	$17,565,058.04
Total Emissions Cost	$11,286,808.44
Total Emission	418029.94 Metric Tons CO_2e
Plot	

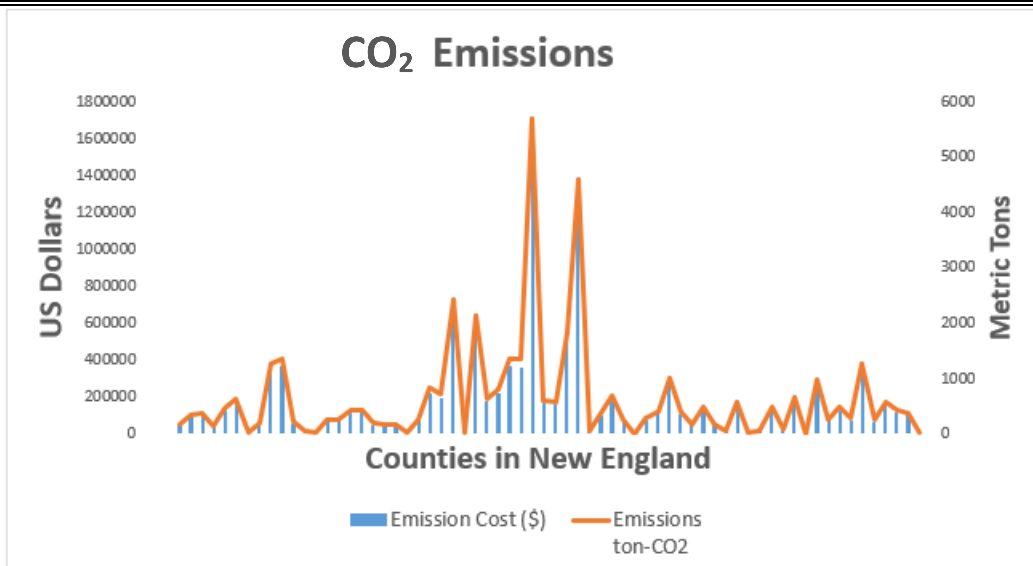
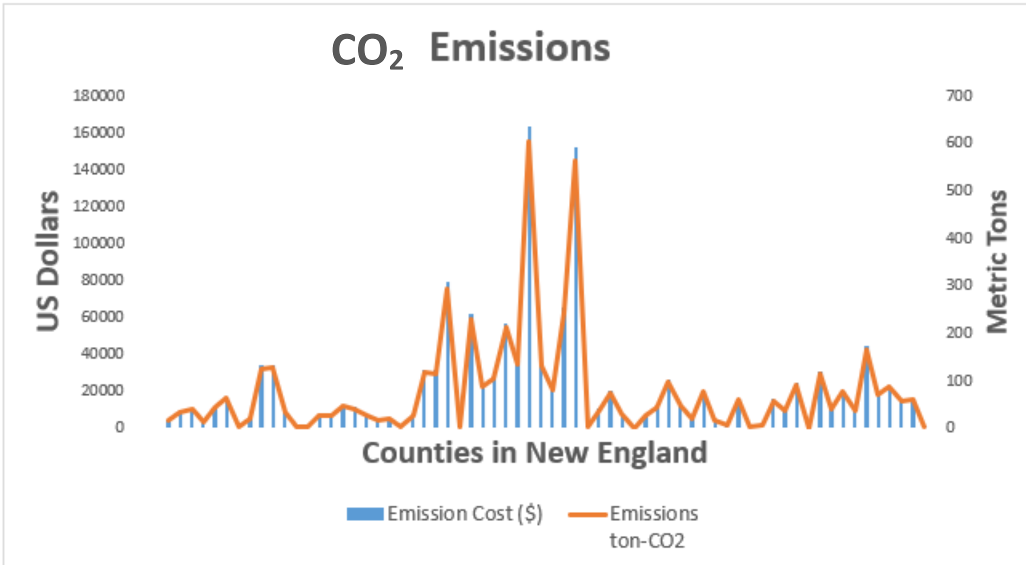


Table 5.4.8.2: Emissions in Type 2 vehicle	
Parameters	
Transport Cost ($/mile) - $2.38 /mile	Number of Households (units) - 50
Storage cost ($) - $0.69	**Capacity of the vehicle - 720,000 lbs.**
Cost of recycling ($/US ton) - $120	Percentage of capacity used - 20%
Incentive Cost ($ / Household / Month) - $0	Distance negotiated - No
Radius of coverage – 5 miles	**Type of vehicle (for emission cost) – Type 2**
Results	

Total Cost	$5,881,016.13
Total Margin	$40,561,827.65
Total Emissions Cost	$1,368,050.34
Total Emission	50668.53 Metric Tons CO_2e
Plot	

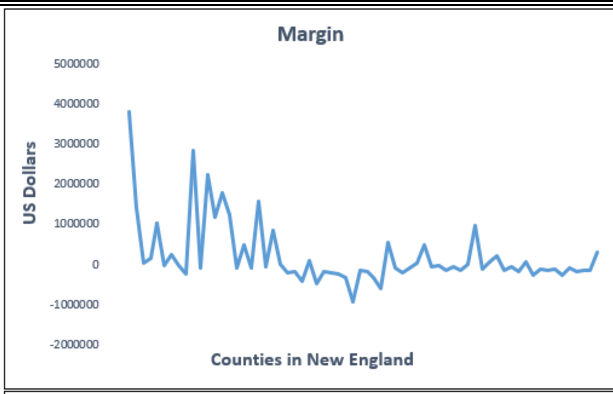


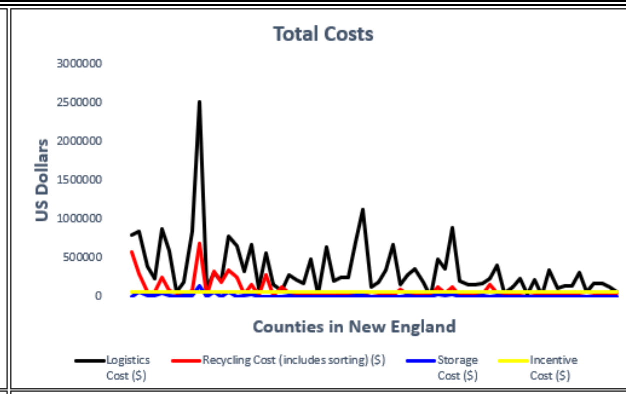
Based on this sensitivity analysis we can clearly see that the emissions are lower if we use the larger vehicle.

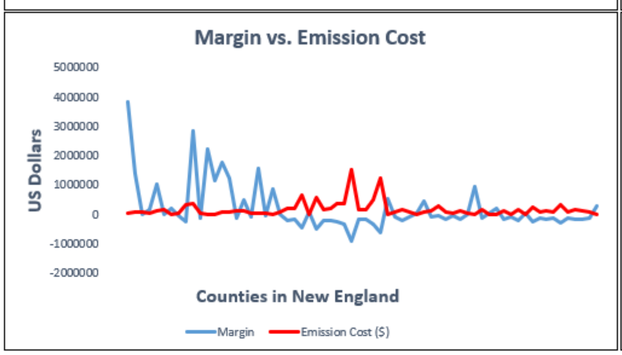
5.4.9 Impact of Incentives

In this research we have always considered that 100% of the post-consumer plastic sold is collected using the take-back process described in Chapter 2. This is primarily due to lack of data describing the relationships between the actual post-consumer collections and other tangible incentives that drive this behavior and enable the actor company to perform this take-back process. In this scenario, we will test our model cost with a $100 per household per month incentive to get better collection rates from that household. The incentives considered in this case are static incentives and results in a flat increase in the overall cost. This investment primarily incentivizes better collection rates, and create awareness about the company's environmental prerogatives.

Table 5.4.9: Impact of customer incentives	
Parameters	
Transport Cost ($/mile) - $2.38 /mile	Number of Households (units) - 50
Storage cost ($) - $0.69	Capacity of the vehicle - 3,500 lbs.
Cost of recycling ($/US ton) - $120	Percentage of capacity used - 20%
Incentive Cost ($ / Household / Month) - $100	Distance negotiated - No
Radius of coverage – 5 miles	Type of vehicle (for emission cost) – Type 1
Results	
Total Cost	$ 32,837,785.74
Total Margin	$ 13,605,058.04
Total Emissions Cost	$ 11,286,808.44
Plots	







6. Discussion

After understanding the results from Initial Data Analysis, Optimized Routes, Margin and Cost Analysis, and Scenario-based Sensitivity Analysis, we now discuss the results. This chapter will cover three sections: (1) A sensitivity parameter-based analysis of the result, (2) Stakeholder incentive analysis, and (3) Recommendations.

This project investigates the potential for an e-commerce-based, reverse logistics mechanism to improve take-back of used plastic packaging from the end consumers to the source or value generation point, such that the cost of logistics will be less than the combined value of cost of production of plastic, value generated from optimized take-back, value of the intangible brand value improvement, and overall cost of responsibility to manage waste management.

The current model and contribution are focused on CPG industry data extrapolated from the data provided by a CPG company in the North American region. While conducting this research we have focused on the New England region to execute the model and analyze the results. This research, however, is not bounded by any company periphery or geographic region and can be extended to other organizations and regions with finite additional varying parameters.

6.1 Sensitivity Parameter-Based Analysis of the Results

Based on the sensitivity analysis conducted in Section 5.4, we understood how the system behaves while we use different parameters to effect change in the system cost and behavior. We comment on some of the observations from the sensitivity analysis, which are significant.

6.1.1 Impact of the choice of type of vehicle on logistics cost

The Type 1 vehicle considered as the base case in the sensitivity analysis performed is the generic van (capacity ≤ 3.5 tons). In our case we considered the vehicle of capacity 3,500 lbs. which is a generic urban logistics vehicle used by prominent logistics players. In our analysis we found that if we use the Type 1 vehicle, we end up making a greater number of trips compared to when we use the Type 2 vehicle – a larger truck (capacity ≥ 70 ton). We make a smaller number of trips when we use the larger truck, in which case the difference in the profit margin is approximately $23 million. The bigger the trucks the higher the profits.

6.1.2 Impact of percentage capacity utilization of the vehicle used on logistics cost

Similar to the discussion in Section 6.1.1, we studied the change in logistics cost based on percentage capacity utilization of the vehicle used on logistics cost. We understand that reducing the percentage capacity will increase the number of trips. This can be grasped in a similar vein as reducing the overall capacity of the vehicle. In our sensitivity analysis we test our data with a 5% capacity utilization of the Type 1 vehicle. This simulation makes the profit margin go negative, generating a significant loss of $51.76 million. Increasing the amount of plastic, a vehicle takes back increases profits.

6.1.3 Impact of vehicle type on emissions

Emissions is an important consideration while analyzing a network design approach to a problem. This is more important in this case as we try to find a solution to an environmentally detrimental problem, primality to improve the quality of the environment. We need to be careful that, while solving one problem we are not introducing new ones. The case of emissions is similar in this context. While we are trying to reduce the global plastic waste, we do not want to increase the systems impact on the climate as a result.

We assess this in our sensitivity analysis through analyzing the carbon intensity of the type of vehicle used. We find that, based on the average emissions data from the GLEC Framework, the Type 1 vans are approximately nine times as harmful as the Type 2 vehicles. Based on the study we conclude it is better to use the Type 2 vehicle for all the line-haul type distances. Higher capacity vehicles cause lower emissions.

6.1.4 Impact of paying for the complete distance rather than Leg 2

In this solution design, we propose that the 3PL providers pick up the post-consumer plastic after doing deliveries from the same households or apartments. This is an optimal approach and removes additional round trips from the overall process, thereby increasing efficiency and reducing cost. However, if the CPG company pays for both the legs of the transportation journey of the vehicle from the County to the Amazon warehouse (Leg 1) and from the Amazon warehouse to the MRF (Leg 2), then the CPG company is essentially paying for half of the delivery trip for Amazon. The CPG company should not do that and instead negotiate to pay for only the second leg of the journey.

We performed sensitivity analysis for this mode of operation in Section 5.4.4 and found that if the CPG company pays only for the Leg 2 section of the journey, then the profit margin almost doubles to $32 million.

6.2 Stakeholder Incentive Analysis

Every system has stakeholders. Stakeholders are the major actors of an underlying system who interact with the system either actively or passively. Stakeholders are the most important piece for the operability and effectiveness of the system from both a process and a cost standpoint

(Veiga, 2013). In this project, the stakeholders are the consumer of the products, the third-party logistics (3PL) provider, and the MRFs.

We briefly describe the stakeholders and their actions as the following:

6.2.1 Consumers

The end consumer of CPG products is the start of the reverse supply chain of plastic waste. The consumer uses the product and creates the waste, which needs to be routed and recycled. Consumers are the actors who take part in the take-back process by facilitating the pickup of the plastic waste by a 3PL provider or mail them. But before this, an aware consumer might already be recycling properly, without contaminating the packaging or throwing it out in the trash. Why would the consumer take on this extra task – what incentivizes him or her?

1. Consumer is motivated to act as a responsible citizen to reduce plastic pollution through superior waste management. Both incentives and information can be a driver of recycling behavior for the consumers, however, dissemination of information seems to have longer-term effects than incentives (both positive in terms of rewards, and negative in terms of punishment payment) (Iyer & Kashyap, 2007).
2. Consumer coupon incentives had been useful in the 1990s for the recycling of the aluminum cans (Allen, Davis, & Soskin, 1993) and similar structure is also used in Finland for plastic and has been received with high enthusiasm (Abila & Kantola, 2019).
3. It has also been seen that the payment by weight for recycling yields better results than a flat fee for municipal solid waste (MSW) (Thøgersen, 2003). However, this is not the case in the current scenario for MSW since the plastic-import ban by China because recycling

is broken in the US (Corkery, 2019). But if an entity chooses to facilitate the take-back process for post-consumer plastic this incentive scheme will become effective again.

4. An empirical study has estimated the willingness to pay (WTP) for the consumers for recycling initiatives to be $2.29 (after adjusting bias). This estimation is based on a survey conducted in a southeastern US neighborhood. This study also indicates the long-term ineffectiveness of the incentive program because it inures the group of people considered in the study. (Koford, Blomquist, Hardesty, & Troske, 2012)

Based on these studies, we can conclude that the CPG companies can employ a low-value incentive structure for a short period of time, to encourage consumer participation in the plastic waste take-back process, while raising awareness at the same time. Thereby the incentives can wane out with time, as the process solidifies.

6.2.2 3rd Party Logistics Providers

In an e-commerce-based take-back mechanism, the major cost of the overall process is logistics. The total logistics cost includes transportation cost, sorting and handling cost, and the collection cost. Based on the model, the consumer either hands in the waste to an e-commerce 3PL provider or mails it directly to the warehouse of the 3PL provider. This incurs cost at the 3PL provider end, and the same must be incurred by the CPG company to enable the take-back process. Here the incentives are the cost of the processes charged by the 3PL provider. However, there is a possibility that the CPG companies could convince the 3PL providers to reduce the cost over time because of the gains through goodwill by aiding the recycling of plastic (Srinivasan & Singh, 2010) and also reduce the logistics cost by committing to long-term contracts (Sink, Langley, & Gibson, 1996).

6.2.3 Material Recovery Facility (MRF)

The final, and the culminating stakeholder in the system is the MRF, who has the final responsibility of preparing, processing and recycling the collected solid plastic waste from the consumer at the end of the supply chain (Pressley, Levis, Damgaard, Barlaz, & DeCarolis, 2015). The several processes as mentioned in Section 4.5 incur a variety of costs, which include the fixed cost of the systems, labor cost and variable operations cost (Chang & Wang, 1995). This cost has to be borne by the party which wants control of the recycled plastic at the end of the recycling process, which in this case is the CPG company.

The implications of the stakeholder analysis are primarily twofold: (1) Improving the collection percentage of the post-consumer plastic, and (2) maximizing the addressable market to reap maximum returns.

In our model we have considered a static cost of incentives which are not tied with the percentage of the post-consumer plastic collected. Also, in our model, this take-back process assumes 100% conversion of all the plastic sold as CPG products into post-consumer plastic and a 100% of that is collected using the take-back process. This assumption, however, is untrue in some circumstances, such as where the consumer is not a responsible recycler in this system. That is to say that she doesn't give back the used plastic through this process but produces additional waste. In such situations, incentives have been proven helpful. The incentive can be designed as a dollar amount to each household who is responsible actors in this system and can enable higher collection rates of post-consumer plastic. Other actors such as the 3PL providers are important stakeholders and several decisions are dependent on pricing and other commercial terms.

In conclusion to this analysis of stakeholder incentives, we understand that even though initially the consumers can be enticed with monetary benefits, it is not required in the longer term.

This can be explained – as the consumers get habitually inclined to participating in the take-back process, also we find that there is already a WTP towards a plastic-free society. Of the next two costs, viz. the 3PL provider costs and MRF costs: The 3PL costs are more dominant, compared to the costs incurred at the MRFs (Chang, Davila, Dyson, & Brown, 2005). Therefore, the major cost component or stakeholder incentive for the CPG company is the cost incurred for the services procured from the 3PL provider, which can further be reduced through long-term contracts (Sink et al., 1996) and bulk deliveries (Goldsby & Closs, 2000).

6.3 Recommendation

Based on the discussion in Section 6.1 and 6.2 we are now well placed to make strategic recommendations to the CPG company.

6.3.1 Best Case Scenario

To maximize the profits when using e-commerce-based reverse logistics channel approach to take-back of post-consumer plastic, the CPG company should use a Type 2 vehicle at 20% capacity utilization. This recommendation is based upon the results as seen in Section 5.4.5. The profit margin is slightly lower than utilizing 40%, but realistically it is difficult to acquire 40% of a vehicle for plastic-waste collection purposes in a real-world reverse logistics process. This selection also minimizes the emissions.

6.3.2 Worst Case Scenario

To maximize the profits when using e-commerce-based reverse logistics channel approach to take-back of post-consumer plastic, CPG company should not use of Type 1 vehicles at 5% capacity utilization, as this will generate heavy losses of approximately $50 million annually. This recommendation is based upon the results as seen in Section 5.4.6. This process is the most harmful for the environment in terms of emissions with an estimated 418,000 ton-CO_2.

Based on these scenarios analyzed in this project, we recommend breaking down the transportation based on the vehicle types for the different legs of the network, by using Type 1 vehicle in the first leg and the Type 2 vehicle in the second leg.

6.4 Contribution

The major contributions of this thesis are primarily at the juncture where sustainability meets process improvements. At a time, when recycling is of utmost importance, there is a need for a process change in the collection of post-consumer plastic to increase the amount of plastic collected for recycling, while creating an economically, socially, and environmentally feasible process for the CPG companies. This thesis contributes to the existing literature by defining both quantitatively and qualitatively the use of existing e-commerce reverse logistics channels to take back post-consumer plastics.

In doing so quantitatively, we contribute by proposing a MILP-based network design model (as described in Section 4.4) to optimize the cost of operations (as described in Section 4.1 (8)), and by designing a total cost equation (as described in Section 4.5) to calculate the profit margin of the company facilitating this process, thereby assessing its economic feasibility.

Using the quantitative analysis and corresponding data as a foundation for scenario-based sensitivity analysis (as described in Section 5.4), this thesis contributes qualitatively by designing a tool to assess the economic and environmental feasibility of the process at various scenarios by changing different parameters affecting the system overall.

7. Conclusion

This research vividly explains how a model leveraging an e-commerce-based reverse logistics channel can facilitate an economically viable take-back process for post-consumer plastic while keeping emissions minimal and adding to the value of the CPG companies. We started to dive into the problem after stating a research and proving the viability of that idea. After performing a rigorous literature review it was clear that e-commerce reverse logistics channel has never been used to take back post-consumer plastic directly from households while simultaneously performing e-commerce deliveries. This notion as substantiated by the literature review was very valuable while performing this research, because we know that the e-commerce reverse logistics network is already set up around us and can be easily leveraged to facilitate this process.

We made some assumptions along the way, which were:

(1) We considered 100% collection rate of post-consumer plastic which enabled us to consider the normalized sales data directly as our working demand for the post-consumer plastic.

(2) We assumed that this process can access a percentage of space in the vehicles used for transportation, and that the 3PL providers will make room for post-consumer plastic and prevent any contamination of new products.

(3) We also made a similar assumption about warehouses freeing up a percentage of their capacity to consolidate the post-consumer plastic from different counties.

(4) Even though we are aware the other regions might look very different in terms of demographics and geographic placement of MRFs and Amazon warehouses, it is important to note that this model will correctly point out the feasibility of effecting this take-back process. Here we assume that this process will render a positive outcome as we see in the New England region.

Further research is suggested, particularly around the following items:

(1) Understanding the relationship of the stakeholder initiatives with the post-consumer plastic collection, trucking price negotiation, symbiotic relationships with competitors.

(2) Defining metrics to quantitatively understand the stakeholder incentives as a variable in the model.

(3) Understanding the environmental value in greater depth from an economic standpoint. This entails an understanding of the monetary implications of brand value improvement, cost of mitigating plastic pollution, attainability of sustainable initiatives, and using new processes as a step towards contributing to the United Nations Sustainable Development goals.

(4) Expanding this study to other types of wastes and assessing if an e-commerce based closed-loop supply chain would be feasible for take-back of other types of post-consumer wastes such as glass, cardboard, and aluminum using the model and techniques proposed in this thesis.

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Appendix

This appendix lists tables depicting some of the relevant, directly applicable data analyses which enabled us to perform the scenario-based sensitivity analysis. The results from the scenario-based analysis were then used to understand the pros and cons of the process and make effective recommendations, substantiating the claims made in this research. The lists included in this Appendix are: (1) Amount of Plastic Generated by County – This table shows the plastic consumption by county. This value is obtained by multiplying the normalizing parameter with the CPG sales information. The normalizing parameter is calculated as mentioned in Section 4.2.4; (2) County ID Mapping – This table shows the IDs assigned to the counties to achieve consistency in analysis; (3) MRF ID Mapping - This table shows the IDs assigned to the MRFs to achieve consistency in analysis; (4) Amazon Warehouse ID Mapping - This table shows the IDs assigned to the Amazon Warehouses to achieve consistency in analysis; (5) Cost, Price and Margin Calculations – This table focuses on actual calculation of cost, total price of virgin plastic, and final calculation of the profit margin as described in Section 4.5; and (6) Distance Matrix – The distance matrix depicts the output from running the optimization model as described in Section 4.4. This table contains both direct distances between a county and an MRF, and the aggregated distance where a consolidator is involved.

A. Amount of Plastic Generated by County

States and Counties	Normalizing Parameter	Total (Metric Tons)	PET (Metric Tons)	PP (Metric Tons)	HDPE (Metric Tons)	LDPE (Metric Tons)
Connecticut	0.019652	10519.91474	4333.255	5989.648	192.9864	4.024888
Fairfield County	0.008191	4384.792497	1806.139	2496.538	80.43843	1.677609
Hartford County	0.004165	2229.707805	918.4383	1269.513	40.90369	0.85308

Litchfield County	0.000846	453.050442	186.6159	257.9501	8.311149	0.173336
Middlesex County	0.000804	430.22451	177.2137	244.9538	7.892411	0.164603
New Haven County	0.003495	1871.089882	770.7201	1065.329	34.32489	0.715873
New London County	0.001137	608.891171	250.8082	346.68	11.17003	0.23296
Tolland County	0.000615	329.067737	135.5462	187.3589	6.036703	0.1259
Windham County	0.000398	213.023454	87.74643	121.2876	3.907887	0.081502
Maine	0.004709	2520.868176	1038.37	1435.289	46.24499	0.964477
Androscoggin County	0.000322	172.205456	70.9331	98.04739	3.159086	0.065885
Aroostook County	0.000199	106.579298	43.90105	60.68229	1.955183	0.040777
Cumberland County	0.001321	706.895936	291.1773	402.4803	12.96791	0.270456
Franklin County	0.000083	44.389575	18.2845	25.27377	0.814321	0.016983
Hancock County	0.000202	108.183979	44.56203	61.59594	1.984621	0.041391
Kennebec County	0.000395	211.325893	87.04719	120.3211	3.876745	0.080853
Knox County	0.00015	80.222212	33.04431	45.67555	1.471666	0.030693
Lincoln County	0.000126	67.370964	27.75075	38.35852	1.235911	0.025776
Oxford County	0.000158	84.31591	34.73054	48.00635	1.546764	0.032259
Penobscot County	0.000457	244.697155	100.7931	139.3215	4.488936	0.09362
Piscataquis County	0.000046	24.838871	10.23137	14.14233	0.455666	0.009503
Sagadahoc County	0.000132	70.426296	29.00927	40.09812	1.291961	0.026945
Somerset County	0.000139	74.300367	30.60504	42.30387	1.36303	0.028427
Waldo County	0.000117	62.530157	25.75678	35.60235	1.147107	0.023924
Washington County	0.000092	48.9947	20.18139	27.89576	0.898801	0.018745
York County	0.000772	413.519708	170.3328	235.4428	7.585963	0.158211
Massachusetts	0.035595	19054.98927	7848.935	10849.2	349.5612	7.290382
Barnstable County	0.001148	614.428628	253.0891	349.8328	11.27161	0.235079
Berkshire County	0.000514	274.955104	113.2567	156.5492	5.044014	0.105197
Bristol County	0.002195	1174.963086	483.9787	668.9803	21.55454	0.449537
Dukes County	0.000117	62.591298	25.78196	35.63716	1.148229	0.023947
Essex County	0.00384	2055.56677	846.7079	1170.363	37.7091	0.786454
Franklin County	0.000279	149.464324	61.56581	85.09943	2.741903	0.057185
Hampden County	0.001732	927.333961	381.9779	527.9895	17.01182	0.354795
Hampshire County	0.000615	329.265189	135.6275	187.4714	6.040326	0.125976

Middlesex County	0.009734	5210.968774	2146.449	2966.932	95.59452	1.993701
Nantucket County	0.000101	54.133212	22.298	30.82144	0.993066	0.020711
Norfolk County	0.004683	2507.020481	1032.666	1427.404	45.99095	0.959179
Plymouth County	0.002516	1347.059773	554.867	766.9658	24.71163	0.515381
Suffolk County	0.004713	2522.997363	1039.247	1436.501	46.28405	0.965291
Worcester County	0.003407	1823.996239	751.3218	1038.516	33.46097	0.697856
New Hampshire	0.005982	3202.106303	1318.979	1823.16	58.74221	1.225116
Belknap County	0.000268	143.560208	59.13384	81.73785	2.633593	0.054926
Carroll County	0.000207	110.747032	45.61778	63.05524	2.031639	0.042371
Cheshire County	0.000286	153.097069	63.06217	87.16778	2.808545	0.058574
Coos County	0.000098	52.458063	21.60799	29.86767	0.962336	0.02007
Grafton County	0.00039	208.92286	86.05735	118.9529	3.832662	0.079933
Hillsborough County	0.001827	977.874737	402.7961	556.7655	17.93898	0.374132
Merrimack County	0.00063	337.119998	138.863	191.9436	6.184421	0.128981
Rockingham County	0.001642	878.977939	362.0595	500.4574	16.12473	0.336294
Strafford County	0.000473	253.367957	104.3647	144.2583	4.648001	0.096938
Sullivan County	0.00016	85.893859	35.38051	48.90477	1.575711	0.032863
Rhode Island	0.004172	2233.49857	919.9997	1271.671	40.97323	0.85453
Bristol County	0.000276	147.653162	60.81977	84.06822	2.708677	0.056492
Kent County	0.000703	376.497393	155.0829	214.3636	6.906794	0.144047
Newport County	0.000408	218.33292	89.93345	124.3106	4.005288	0.083534
Providence County	0.002203	1179.228504	485.7357	671.4089	21.63279	0.451169
Washington County	0.000582	311.80169	128.4341	177.5283	5.71996	0.119294
Vermont	0.002441	1306.684967	538.2362	743.9779	23.97096	0.499934
Addison County	0.000138	73.761227	30.38296	41.9969	1.35314	0.028221
Bennington County	0.00014	74.725284	30.78007	42.5458	1.370825	0.02859
Caledonia County	0.00009	48.12501	19.82316	27.40059	0.882847	0.018412
Chittenden County	0.000721	386.067384	159.0249	219.8124	7.082354	0.147708
Essex County	0.000016	8.665834	3.569541	4.934004	0.158974	0.003316
Franklin County	0.000164	87.997921	36.2472	50.10275	1.61431	0.033668
Grand Isle County	0.00003	16.187836	6.667927	9.216752	0.296964	0.006193
Lamoille County	0.000098	52.550046	21.64587	29.92004	0.964024	0.020105

Orange County	0.000098	52.659606	21.691	29.98242	0.966033	0.020147
Orleans County	0.000084	45.098095	18.57634	25.67718	0.827318	0.017254
Rutland County	0.000221	118.254291	48.71009	67.3296	2.169359	0.045244
Washington County	0.000252	134.914469	55.57258	76.81528	2.474988	0.051618
Windham County	0.000157	83.86575	34.54512	47.75004	1.538506	0.032087
Windsor County	0.000231	123.754337	50.97561	70.46112	2.270257	0.047348

B. County ID Mapping

State	County ID	County	State	County ID	County
CT	CTY_CT_1	Fairfield County	ME	CTY_ME_12	Androscoggin County
CT	CTY_CT_2	Hartford County	ME	CTY_ME_13	Kennebec County
CT	CTY_CT_3	Litchfield County	ME	CTY_ME_14	Lincoln County
CT	CTY_CT_4	Middlesex County	ME	CTY_ME_15	Oxford County
CT	CTY_CT_5	New Haven County	NH	CTY_NH_1	Strafford County
CT	CTY_CT_6	New London County	NH	CTY_NH_2	Sullivan County
CT	CTY_CT_7	Tolland County	NH	CTY_NH_3	Hillsborough County
CT	CTY_CT_8	Windham County	NH	CTY_NH_4	Merrimack County
MA	CTY_MA_1	Barnstable County	NH	CTY_NH_6	Rockingham County
MA	CTY_MA_2	Berkshire County	NH	CTY_NH_7	Carroll County
MA	CTY_MA_3	Bristol County	NH	CTY_NH_8	Cheshire County
MA	CTY_MA_4	Dukes County	NH	CTY_NH_9	Coos County
MA	CTY_MA_5	Essex County	NH	CTY_NH_10	Grafton County
MA	CTY_MA_6	Franklin County	NH	CTY_NH_11	Belknap County
MA	CTY_MA_7	Hampden County	RI	CTY_RI_1	Newport County
MA	CTY_MA_8	Hampshire County	RI	CTY_RI_2	Providence County
MA	CTY_MA_10	Middlesex County	RI	CTY_RI_3	Washington County
MA	CTY_MA_11	Nantucket County	RI	CTY_RI_4	Bristol County
MA	CTY_MA_12	Norfolk County	RI	CTY_RI_5	Kent County

MA	CTY_MA_13	Plymouth County	VT	CTY_VT_1	Windsor County
MA	CTY_MA_14	Suffolk County	VT	CTY_VT_2	Orleans County
MA	CTY_MA_15	Worcester County	VT	CTY_VT_3	Windham County
ME	CTY_ME_1	Waldo County	VT	CTY_VT_4	Franklin County
ME	CTY_ME_2	Washington County	VT	CTY_VT_5	Grand Isle County
ME	CTY_ME_3	York County	VT	CTY_VT_6	Lamoille County
ME	CTY_ME_4	Penobscot County	VT	CTY_VT_7	Bennington County
ME	CTY_ME_5	Piscataquis County	VT	CTY_VT_8	Caledonia County
ME	CTY_ME_6	Sagadahoc County	VT	CTY_VT_9	Chittenden County
ME	CTY_ME_7	Somerset County	VT	CTY_VT_10	Essex County
ME	CTY_ME_8	Aroostook County	VT	CTY_VT_11	Addison County
ME	CTY_ME_9	Cumberland County	VT	CTY_VT_12	Rutland County
ME	CTY_ME_10	Franklin County	VT	CTY_VT_13	Washington County
ME	CTY_ME_11	Hancock County	VT	CTY_VT_14	Orange County

C. MRF ID Mapping

State	MRF ID	MRF Address
CT	MRF_CT_1	61 Crescent St, Stamford, CT 06906, USA
CT	MRF_CT_2	100 3rd St, Bridgeport, CT 06607, USA
CT	MRF_CT_3	90 Oliver Terrace, Shelton, CT 06484, USA
CT	MRF_CT_4	283 White St, Danbury, CT 06810, USA
CT	MRF_CT_5	174 Edgewood Ave, New Britain, CT 06051, USA
CT	MRF_CT_6	1680 W Main St, Windham, CT 06280, USA
CT	MRF_CT_7	143 Murphy Rd, Hartford, CT 06114, USA
CT	MRF_CT_8	143 Murphy Rd, Hartford, CT 06114, USA
MA	MRF_MA_1	45 Kings Hwy, West Wareham, MA 02576, USA
MA	MRF_MA_2	70 Battles St, Brockton, MA 02302, USA

MA	MRF_MA_3	Main/Cumberland, Springfield, MA 01107, USA
MA	MRF_MA_4	13 Robbie Rd, Avon, MA 02322, USA
MA	MRF_MA_5	1 Hardscrabble Rd, Auburn, MA 01501, USA
MA	MRF_MA_6	30 Hopkinton Rd, Westborough, MA 01581, USA
MA	MRF_MA_7	40 Bunker Hill Industrial Park, Boston, MA 02129, USA
MA	MRF_MA_8	73 Newbury St, Peabody, MA 01960, USA
MA	MRF_MA_9	31 High St, North Billerica, MA 01862, USA
ME	MRF_ME_1	2300 Congress St, Portland, ME 04102, USA
ME	MRF_ME_2	424 River Rd, Lewiston, ME 04240, USA
NH	MRF_NH_1	12 Brown Rd, Newport, NH 03773, USA
RI	MRF_RI_1	98 Taylor Rd, Johnston, RI 02919, USA
VT	MRF_VT_1	127 Dorr Dr, Rutland, VT 05701, USA
VT	MRF_VT_2	Avenue D, Williston, VT 05495, USA

D. Amazon Warehouse ID Mapping

State	Amazon ID	Amazon Fulfilment Center Address
NH	AMZ_1	10 State St, Nashua, NH 03063, USA
MA	AMZ_2	1180 Innovation Way, Fall River, MA 02720, USA
CT	AMZ_3	29 Research Pkwy, Meriden, CT 06450, USA
CT	AMZ_4	409 Washington Ave, North Haven, CT 06473, USA
CT	AMZ_5	801 Day Hill Rd, Windsor, CT 06095, USA
MA	AMZ_6	Amazon Fulfillment Center, 1000 Technology Center Dr, Stoughton, MA 02072, USA

E. Cost, Price and Margin Calculation

			Costs				Price	Profit		
CTY_ID	Total (miles)	Plastic Waste (Lbs.)	Logistics Cost ($)	Recycling Cost (includes sorting) ($)	Storage Cost ($)	Incentive Cost ($)	Total P_virgin ($)	Margin ($)	Emissions g-CO2	Emission Cost ($)
CTY_CT_1	12.14	9666801.23	$ 798,286.16	$ 580,008.07	$ -	$ 6,000.00	$ 5,254,290.00	$ 3,869,995.77	1622887724	43817.97
CTY_CT_2	25.04	4915658.42	$ 837,109.40	$ 294,939.51	$ 56,284.55	$ 6,000.00	$ 2,671,855.38	$ 1,477,521.93	3509934137	94768.22
CTY_CT_3	57.59	998804.07	$ 391,270.80	$ 59,928.24	$ 11,436.36	$ 6,000.00	$ 542,889.64	$ 74,254.23	3773193254	101876.22
CTY_CT_4	35.21	948481.56	$ 227,172.07	$ 56,908.89	$ 10,860.16	$ 6,000.00	$ 515,537.36	$ 214,596.23	1339323127	36161.72
CTY_CT_5	30.95	4125042.18	$ 868,234.10	$ 247,502.53	$ 47,231.95	$ 6,000.00	$ 2,242,124.08	$ 1,073,155.50	4499554359	121487.97
CTY_CT_6	64.56	1342373.65	$ 589,468.59	$ 80,542.42	$ 15,370.25	$ 6,000.00	$ 729,633.34	$ 38,252.08	6372732973	172063.79
CTY_CT_7	12.45	725469.31	$ 61,483.71	$ 43,528.16	$ -	$ 6,000.00	$ 394,321.36	$ 283,309.48	128217831.6	3461.88
CTY_CT_8	58.65	469635.77	$ 187,450.66	$ 28,178.15	$ 5,377.35	$ 6,000.00	$ 255,265.67	$ 28,259.51	1841078799	49709.13
CTY_MA_1	90.65	1354581.64	$ 835,193.11	$ 81,274.90	$ 15,510.03	$ 6,000.00	$ 736,268.87	$ (201,709.17)	12678154382	342310.17
CTY_MA_10	32.14	11488205.98	$ 2,510,995.76	$ 689,292.36	$ 131,540.57	$ 6,000.00	$ 6,244,295.75	$ 2,906,467.06	13514199858	364883.40
CTY_MA_11	124.62	119343.16	$ 101,436.02	$ 7,160.59	$ 1,366.49	$ 6,000.00	$ 64,867.74	$ (51,095.35)	2116904647	57156.43
CTY_MA_12	8.11	5527027.49	$ 304,932.22	$ 331,621.65	$ 63,284.76	$ 6,000.00	$ 3,004,158.73	$ 2,298,320.10	414077078.7	11180.08
CTY_MA_13	9.91	2969754.92	$ 200,160.42	$ 178,185.30	$ -	$ 6,000.00	$ 1,614,179.62	$ 1,229,833.91	332060735.9	8965.64
CTY_MA_14	20.41	5562250.45	$ 772,085.74	$ 333,735.03	$ 63,688.06	$ 6,000.00	$ 3,023,303.80	$ 1,847,794.97	2638662029	71243.87
CTY_MA_15	23.80	4021218.59	$ 650,834.49	$ 241,273.12	$ -	$ 6,000.00	$ 2,185,691.85	$ 1,287,584.24	2593514694	70024.90
CTY_MA_2	79.32	606171.52	$ 327,135.48	$ 36,370.29	$ 6,940.70	$ 6,000.00	$ 329,478.27	$ (46,968.19)	4345136415	117318.68
CTY_MA_3	38.00	2590347.12	$ 669,484.38	$ 155,420.83	$ 29,659.61	$ 6,000.00	$ 1,407,956.43	$ 547,391.61	4260258173	115026.97
CTY_MA_3	106.60	137990.03	$ 100,289.24	$ 8,279.40	$ 1,579.99	$ 6,000.00	$ 75,003.06	$ (41,145.58)	1790380891	48340.28
CTY_MA_4	18.18	4531743.61	$ 560,343.62	$ 271,904.62	$ -	$ 6,000.00	$ 2,463,182.45	$ 1,624,934.21	1705804383	46056.72
CTY_MA_5	67.30	329512.04	$ 150,968.43	$ 19,770.72	$ 3,772.93	$ 6,000.00	$ 179,102.87	$ (1,409.21)	1701470538	45939.70
CTY_MA_5	5.20	2044419.00	$ 72,302.60	$ 122,665.14	$ -	$ 6,000.00	$ 1,111,222.84	$ 910,255.10	62910347.34	1698.58
CTY_MA_6	55.66	725904.62	$ 274,915.22	$ 43,554.28	$ 8,311.65	$ 6,000.00	$ 394,557.96	$ 61,776.82	2562670547	69192.10
CTY_MA_7	228.49	137855.23	$ 214,738.54	$ 8,271.31	$ 1,578.45	$ 6,000.00	$ 74,929.79	$ (155,658.51)	8216737732	221851.92
CTY_MA_8	251.55	97862.14	$ 168,003.99	$ 5,871.73	$ 1,120.53	$ 6,000.00	$ 53,191.96	$ (127,804.29)	7077412774	191090.14
CTY_ME_1	297.64	238504.56	$ 483,433.35	$ 14,310.27	$ 2,730.89	$ 6,000.00	$ 129,636.69	$ (376,837.82)	24096343588	650601.28

CTY_ME_10	11.21	379647.59	$ 28,978.05	$ 22,778.86	$ -	$ 6,000.00	$ 206,353.53	$ 148,596.62	54396349.38	1468.70
CTY_ME_11	199.73	465893.29	$ 633,245.09	$ 27,953.60	$ 5,334.50	$ 6,000.00	$ 253,231.49	$ (419,301.71)	21180724745	571879.57
CTY_ME_12	193.30	148527.37	$ 195,701.14	$ 8,911.64	$ 1,700.65	$ 6,000.00	$ 80,730.52	$ (131,582.90)	6335193456	171050.22
CTY_ME_13	195.35	185884.54	$ 247,398.34	$ 11,153.07	$ 2,128.39	$ 6,000.00	$ 101,035.62	$ (165,644.18)	8093529064	218525.28
CTY_ME_14	330.69	108014.70	$ 243,682.37	$ 6,480.88	$ 1,236.77	$ 6,000.00	$ 58,710.27	$ (198,689.76)	13494819724	364360.13
CTY_ME_15	113.44	911653.82	$ 703,511.74	$ 54,699.23	$ 10,438.48	$ 6,000.00	$ 495,520.02	$ (279,129.43)	13364396486	360838.71
CTY_ME_2	304.14	539464.24	$ 1,116,439.16	$ 32,367.85	$ 6,176.89	$ 6,000.00	$ 293,220.22	$ (867,763.69)	56864282339	1535335.62
CTY_ME_3	311.50	54760.27	$ 116,741.32	$ 3,285.62	$ 627.01	$ 6,000.00	$ 29,764.38	$ (96,889.56)	6089866366	164426.39
CTY_ME_4	179.84	155263.22	$ 190,306.21	$ 9,315.79	$ 1,777.77	$ 6,000.00	$ 84,391.72	$ (123,008.06)	5731397429	154747.73
CTY_ME_5	310.50	163804.08	$ 346,601.26	$ 9,828.24	$ 1,875.57	$ 6,000.00	$ 89,034.01	$ (275,271.05)	18022639003	486611.25
CTY_ME_6	414.13	234966.85	$ 662,681.64	$ 14,098.01	$ 2,690.38	$ 6,000.00	$ 127,713.81	$ (557,756.23)	45959035813	1240893.97
CTY_ME_7	14.96	1558436.92	$ 158,604.00	$ 93,506.22	$ -	$ 6,000.00	$ 847,072.30	$ 588,962.08	397314940.6	10727.50
CTY_ME_8	74.75	558580.07	$ 284,117.87	$ 33,514.80	$ 6,395.77	$ 6,000.00	$ 303,610.43	$ (26,418.02)	3556574714	96027.52
CTY_ME_9	114.06	460595.52	$ 357,530.09	$ 27,635.73	$ 5,273.84	$ 6,000.00	$ 250,351.94	$ (146,087.73)	6829312259	184391.43
CTY_NH_1	82.76	316495.71	$ 178,321.45	$ 18,989.74	$ 3,623.89	$ 6,000.00	$ 172,027.97	$ (34,907.11)	2471440771	66728.90
CTY_NH_10	3.02	189363.32	$ 3,908.31	$ 11,361.80	$ -	$ 6,000.00	$ 102,926.48	$ 81,656.37	1978167.82	53.41
CTY_NH_11	32.90	2155842.20	$ 482,402.42	$ 129,350.53	$ 24,684.51	$ 6,000.00	$ 1,171,785.77	$ 529,348.31	2657634054	71756.12
CTY_NH_2	69.36	743221.49	$ 350,703.61	$ 44,593.29	$ 8,509.93	$ 6,000.00	$ 403,970.37	$ (5,836.45)	4073326344	109979.81
CTY_NH_3	67.71	1937812.34	$ 892,374.69	$ 116,268.74	$ 22,188.05	$ 6,000.00	$ 1,053,277.89	$ 16,446.41	10118060949	273187.65
CTY_NH_4	118.54	244155.12	$ 197,091.47	$ 14,649.31	$ 2,795.59	$ 6,000.00	$ 132,708.00	$ (87,828.37)	3912418282	105635.29
CTY_NH_6	67.75	337520.86	$ 155,668.77	$ 20,251.25	$ 3,864.63	$ 6,000.00	$ 183,455.98	$ (2,328.67)	1766189339	47687.11
CTY_NH_7	193.57	115650.09	$ 152,696.56	$ 6,939.01	$ 1,324.20	$ 6,000.00	$ 62,860.42	$ (104,099.35)	4949919637	133647.83
CTY_NH_8	52.61	481341.12	$ 172,327.92	$ 28,880.47	$ 5,511.38	$ 6,000.00	$ 261,628.00	$ 48,908.23	1518174480	40990.71
CTY_NH_9	12.96	2599750.74	$ 229,124.03	$ 155,985.04	$ -	$ 6,000.00	$ 1,413,067.68	$ 1,021,958.60	497081634.9	13421.20
CTY_RI_1	84.73	687404.24	$ 396,283.41	$ 41,244.25	$ 7,870.82	$ 6,000.00	$ 373,631.48	$ (77,767.00)	5623090026	151823.43
CTY_RI_2	21.97	325519.11	$ 48,686.37	$ 19,531.15	$ -	$ 6,000.00	$ 176,932.55	$ 102,715.03	179093871.8	4835.53
CTY_RI_3	21.92	830033.68	$ 123,777.49	$ 49,802.02	$ -	$ 6,000.00	$ 451,156.24	$ 271,576.73	454290571.9	12265.85
CTY_RI_5	124.43	272831.29	$ 231,156.99	$ 16,369.88	$ 3,123.93	$ 6,000.00	$ 148,294.63	$ (108,356.17)	4816847056	130054.87
CTY_VT_1	186.62	19104.87	$ 24,698.65	$ 1,146.29	$ 218.75	$ 6,000.00	$ 10,384.26	$ (21,679.44)	771881398.6	20840.80
CTY_VT_11	188.47	162615.48	$ 208,859.69	$ 9,756.93	$ 1,861.96	$ 6,000.00	$ 88,387.96	$ (138,090.62)	6591985085	177983.60
CTY_VT_12	4.16	260705.78	$ 7,394.90	$ 15,642.35	$ -	$ 6,000.00	$ 141,703.93	$ 112,666.68	5151217.456	139.08
CTY_VT_13	168.44	297435.14	$ 341,081.51	$ 17,846.11	$ 3,405.65	$ 6,000.00	$ 161,667.80	$ (206,665.47)	9620975711	259766.34
CTY_VT_14	137.32	116094.42	$ 108,738.79	$ 6,965.67	$ 1,329.29	$ 6,000.00	$ 63,101.92	$ (59,931.82)	2500570116	67515.39
CTY_VT_2	203.13	99424.16	$ 137,825.28	$ 5,965.45	$ 1,138.41	$ 6,000.00	$ 54,040.98	$ (96,888.17)	4688519655	126590.03
CTY_VT_3	114.11	184892.11	$ 143,750.36	$ 11,093.53	$ 2,117.02	$ 6,000.00	$ 100,496.20	$ (62,464.71)	2747078681	74171.12
CTY_VT_4	239.82	194001.98	$ 316,949.05	$ 11,640.12	$ 2,221.33	$ 6,000.00	$ 105,447.77	$ (231,362.73)	12729104795	343685.83
CTY_VT_5	242.67	35688.03	$ 59,476.44	$ 2,141.28	$ 408.63	$ 6,000.00	$ 19,397.86	$ (48,628.49)	2417052257	65260.41

CTY_VT_6	206.26	115852.88	$ 162,990.58	$ 6,951.17	$ 1,326.52	$ 6,000.00	$ 62,970.64	$ (114,297.64)	5629988954	152009.70
CTY_VT_7	150.44	164740.86	$ 168,893.45	$ 9,884.45	$ 1,886.29	$ 6,000.00	$ 89,543.19	$ (97,121.00)	4255011139	114885.30
CTY_VT_8	176.06	106097.36	$ 127,444.10	$ 6,365.84	$ 1,214.82	$ 6,000.00	$ 57,668.12	$ (83,356.64)	3757494933	101452.36
CTY_VT_9	10.58	851131.88	$ 61,255.55	$ 51,067.91	$ -	$ 6,000.00	$ 462,623.94	$ 344,300.49	108479314	2928.94

F. Distances Matrix

CTY_ID	MRF_ID	Miles	Final for Cost	Total Distance (including Leg 1)	CTY_ID	AMZ_ID	MRF_ID	Miles
CTY_CT_1	MRF_CT_4	12.14	12.14	12.14	CTY_CT_1	AMZ_4	MRF_CT_3	59.21
CTY_CT_2	MRF_CT_8	14.63	13.19	25.04	CTY_CT_2	AMZ_5	MRF_CT_7	25.04
CTY_CT_3	MRF_CT_4	34.15	13.91	57.59	CTY_CT_3	AMZ_3	MRF_CT_5	57.59
CTY_CT_4	MRF_CT_5	24.15	13.91	35.21	CTY_CT_4	AMZ_3	MRF_CT_5	35.21
CTY_CT_5	MRF_CT_3	22.08	21.26	30.95	CTY_CT_5	AMZ_4	MRF_CT_3	30.95
CTY_CT_6	MRF_CT_6	20.02	13.19	64.56	CTY_CT_6	AMZ_5	MRF_CT_7	64.56
CTY_CT_7	MRF_CT_6	12.45	12.45	12.45	CTY_CT_7	AMZ_5	MRF_CT_7	37.09
CTY_CT_8	MRF_CT_6	16.26	13.19	58.65	CTY_CT_8	AMZ_5	MRF_CT_7	58.65
CTY_MA_1	MRF_MA_1	33.35	27.58	90.65	CTY_MA_1	AMZ_2	MRF_MA_2	90.65
CTY_MA_10	MRF_MA_9	15.41	1.63	32.14	CTY_MA_10	AMZ_6	MRF_MA_4	32.14
CTY_MA_11	MRF_MA_1	67.28	27.58	124.62	CTY_MA_11	AMZ_2	MRF_MA_2	124.62
CTY_MA_12	MRF_MA_4	7.51	1.63	8.11	CTY_MA_12	AMZ_6	MRF_MA_4	8.11
CTY_MA_13	MRF_MA_1	9.91	9.91	9.91	CTY_MA_13	AMZ_2	MRF_MA_2	67.58
CTY_MA_14	MRF_MA_7	3.23	1.63	20.41	CTY_MA_14	AMZ_6	MRF_MA_4	20.41
CTY_MA_15	MRF_MA_6	23.80	23.80	23.80	CTY_MA_15	AMZ_1	MRF_MA_9	80.51
CTY_MA_2	MRF_MA_3	46.54	13.19	79.32	CTY_MA_2	AMZ_5	MRF_CT_7	79.32
CTY_MA_3	MRF_RI_1	28.36	27.58	38.00	CTY_MA_3	AMZ_2	MRF_MA_2	38.00
CTY_MA_4	MRF_MA_1	49.30	27.58	106.60	CTY_MA_4	AMZ_2	MRF_MA_2	106.60
CTY_MA_5	MRF_MA_8	18.18	18.18	18.18	CTY_MA_5	AMZ_1	MRF_MA_9	69.84
CTY_MA_6	MRF_MA_3	34.53	13.19	67.30	CTY_MA_6	AMZ_5	MRF_CT_7	67.30
CTY_MA_7	MRF_MA_3	5.20	5.20	5.20	CTY_MA_7	AMZ_5	MRF_CT_7	39.03
CTY_MA_8	MRF_MA_3	22.89	13.19	55.66	CTY_MA_8	AMZ_5	MRF_CT_7	55.66
CTY_ME_1	MRF_ME_2	71.17	24.10	228.49	CTY_ME_1	AMZ_1	MRF_MA_9	228.49
CTY_ME_10	MRF_ME_2	91.03	24.10	251.55	CTY_ME_10	AMZ_1	MRF_MA_9	251.55
CTY_ME_11	MRF_ME_2	140.32	24.10	297.64	CTY_ME_11	AMZ_1	MRF_MA_9	297.64
CTY_ME_12	MRF_ME_2	11.21	11.21	11.21	CTY_ME_12	AMZ_1	MRF_MA_9	172.44
CTY_ME_13	MRF_ME_2	42.41	24.10	199.73	CTY_ME_13	AMZ_1	MRF_MA_9	199.73
CTY_ME_14	MRF_ME_2	50.45	24.10	193.30	CTY_ME_14	AMZ_1	MRF_MA_9	193.30
CTY_ME_15	MRF_ME_2	52.87	24.10	195.35	CTY_ME_15	AMZ_1	MRF_MA_9	195.35
CTY_ME_2	MRF_ME_2	174.21	24.10	330.69	CTY_ME_2	AMZ_1	MRF_MA_9	330.69
CTY_ME_3	MRF_ME_1	27.41	24.10	113.44	CTY_ME_3	AMZ_1	MRF_MA_9	113.44
CTY_ME_4	MRF_ME_2	146.83	24.10	304.14	CTY_ME_4	AMZ_1	MRF_MA_9	304.14
CTY_ME_5	MRF_ME_2	155.40	24.10	311.50	CTY_ME_5	AMZ_1	MRF_MA_9	311.50
CTY_ME_6	MRF_ME_2	37.45	24.10	179.84	CTY_ME_6	AMZ_1	MRF_MA_9	179.84
CTY_ME_7	MRF_ME_2	136.75	24.10	310.50	CTY_ME_7	AMZ_1	MRF_MA_9	310.50
CTY_ME_8	MRF_ME_2	256.82	24.10	414.13	CTY_ME_8	AMZ_1	MRF_MA_9	414.13
CTY_ME_9	MRF_ME_1	14.96	14.96	14.96	CTY_ME_9	AMZ_1	MRF_MA_9	145.58

CTY_NH_1	MRF_ME_1	53.67	24.10	74.75	CTY_NH_1	AMZ_1	MRF_MA_9	74.75
CTY_NH_10	MRF_NH_1	61.36	24.10	114.06	CTY_NH_10	AMZ_1	MRF_MA_9	114.06
CTY_NH_11	MRF_NH_1	52.30	24.10	82.76	CTY_NH_11	AMZ_1	MRF_MA_9	82.76
CTY_NH_2	MRF_NH_1	3.02	3.02	3.02	CTY_NH_2	AMZ_1	MRF_MA_9	99.76
CTY_NH_3	MRF_MA_9	32.61	24.10	32.90	CTY_NH_3	AMZ_1	MRF_MA_9	32.90
CTY_NH_4	MRF_NH_1	34.83	24.10	69.36	CTY_NH_4	AMZ_1	MRF_MA_9	69.36
CTY_NH_6	MRF_MA_9	36.60	24.10	67.71	CTY_NH_6	AMZ_1	MRF_MA_9	67.71
CTY_NH_7	MRF_ME_1	56.83	24.10	118.54	CTY_NH_7	AMZ_1	MRF_MA_9	118.54
CTY_NH_8	MRF_NH_1	37.70	24.10	67.75	CTY_NH_8	AMZ_1	MRF_MA_9	67.75
CTY_NH_9	MRF_ME_2	96.86	24.10	193.57	CTY_NH_9	AMZ_1	MRF_MA_9	193.57
CTY_RI_1	MRF_RI_1	35.06	27.58	52.61	CTY_RI_1	AMZ_2	MRF_MA_2	52.61
CTY_RI_2	MRF_RI_1	12.96	12.96	12.96	CTY_RI_2	AMZ_2	MRF_MA_2	59.31
CTY_RI_3	MRF_RI_1	34.39	27.58	84.73	CTY_RI_3	AMZ_2	MRF_MA_2	84.73
CTY_RI_4	MRF_RI_1	21.97	21.97	21.97	CTY_RI_4	AMZ_2	MRF_MA_2	42.36
CTY_RI_5	MRF_RI_1	21.92	21.92	21.92	CTY_RI_5	AMZ_2	MRF_MA_2	74.90
CTY_VT_1	MRF_NH_1	27.70	24.10	124.43	CTY_VT_1	AMZ_1	MRF_MA_9	124.43
CTY_VT_10	MRF_VT_2	95.28	24.10	186.62	CTY_VT_10	AMZ_1	MRF_MA_9	186.62
CTY_VT_11	MRF_VT_2	27.10	24.10	188.47	CTY_VT_11	AMZ_1	MRF_MA_9	188.47
CTY_VT_12	MRF_VT_1	4.16	4.16	4.16	CTY_VT_12	AMZ_1	MRF_MA_9	160.90
CTY_VT_13	MRF_VT_2	45.29	24.10	168.44	CTY_VT_13	AMZ_1	MRF_MA_9	168.44
CTY_VT_14	MRF_VT_1	43.79	24.10	137.32	CTY_VT_14	AMZ_1	MRF_MA_9	137.32
CTY_VT_2	MRF_VT_2	67.38	24.10	203.13	CTY_VT_2	AMZ_1	MRF_MA_9	203.13
CTY_VT_3	MRF_VT_1	55.14	24.10	114.11	CTY_VT_3	AMZ_1	MRF_MA_9	114.11
CTY_VT_4	MRF_VT_2	39.52	24.10	239.82	CTY_VT_4	AMZ_1	MRF_MA_9	239.82
CTY_VT_5	MRF_VT_2	42.38	24.10	242.67	CTY_VT_5	AMZ_1	MRF_MA_9	242.67
CTY_VT_6	MRF_VT_2	37.66	24.10	206.26	CTY_VT_6	AMZ_1	MRF_MA_9	206.26
CTY_VT_7	MRF_VT_1	56.68	24.10	150.44	CTY_VT_7	AMZ_1	MRF_MA_9	150.44
CTY_VT_8	MRF_VT_2	81.83	24.10	176.06	CTY_VT_8	AMZ_1	MRF_MA_9	176.06
CTY_VT_9	MRF_VT_2	10.58	10.58	10.58	CTY_VT_9	AMZ_1	MRF_MA_9	196.15

[The End]