Designing an optimization carbon cost network in a reverse supply chain

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ABSTRACT
The US Environmental Protection Agency (EPA) has taken major steps to meet the targets of the Social Cost of Carbon (SC-CO2). In what follows, a research model using the market price for emission allowances per metric ton illustrates how the economic and environment mechanisms of carbon price can be formulated using deterministic and stochastic equilibrium models: the primary concern becomes one of optimal stochastic control. Moreover, this framework allows us to consider the prospective influence of the proposed policy on the profit margins for remanufactured goods, in addition to its performance; further presented is an in-depth study to quantitatively evaluate the model and its performance through the use of Orthogonal Arrays. The results demonstrate that the proposed policy for carbon tax brings about tight constraints on the quantity of carbon emissions produced through supply chain operations; numerical examples are based upon actual locations in the area of Boston.

1. Introduction
Reverse Supply Chain (RSC) is the initiative that provides a key role in the global supply chain for organizations endeavoring to implement environmentally responsible solutions in their management of end-of-life (EOL) products (Alkhayyal & Gupta, 2018a). While many definitions for RSC have been put forward in industry literature, the above-mentioned definition has been optimized herein due to its completeness in the integration of the central elements required for our model. For years, the quantity of consumer-discarded products has been rising, and as a result, we have witnessed an increase in legislative action in countries that require that original equipment manufacturers (OEMs) be held accountable for the processing of end-of-life products. Undoubtedly, consumer awareness of environmental issues has a marked impact on the field of supply chain. The related environmental and economic value of RSC is impacted by the costs and emissions realized during transportation, collection, disassembly, recycling, and disposal of unrecoverable components at recovery facilities (Alkhayyal & Gupta, 2018b; Ilgin & Gupta, 2010).
The world’s finite resources, changing climate, disposal capacities, increasingly large population, improving quality of life for many on the planet, a rise in emissions, and increasing costs of energy, all strengthen the necessity for measures to limit the manufactured effects on ecosystems, and compound the resolve to inspire policymakers. Both corporate and academic institutions, therefore, are motivated to develop strategies on sustainable supply chains and corporate social responsibilities (Carter, 2008; Nagurney, Zugang, & Trisha, 2007; Paul, Kalyan, & Luk, 2005).

Remanufacturing is a process that returns a used product to a new state through the refurbishment, replacement, and reuse of its components defined as ‘A process that brings a used product back to a new state through reuse, refurbishment and replacement of its components’ (Amezquita, Hammond, Salazar, & Bras, 1995). It is a sequence that involves the reprocessing of used products by disassembly, cleaning, inspection, the sorting, repair or replacement of parts (if applicable) and their eventual reassembly for a remanufactured product. Restoration can generate items in a condition that is as good, or even better, than ones considered brand new, and it returns a product to the market with not only the same functionality but an extended life cycle. The recycling of recovered end-of-use products alongside their parts by way of a remanufacturing system would ultimately reduce the industrial and the expense of disposal for material-intensive and heavy machinery and equipment (Carter, 2008; Nagurney et al., 2007; Paul et al., 2005; Seuring, Joseph, Martin, & Purba, 2008).

This dissertation is comprised of an empirical analysis and compilation of five research papers that in concert develop novel and effective approaches to build upon the extant literature on reverse supply chain systems.

To support the consideration undertaken herein, an exhaustive review of extant literature on RSC has been conducted to guide the analysis and structure of the study. RSC is an increasingly prevalent subject in modern research, and comprises many fields, including the handling of EOL products and their processing through collection, transport, recovery, disassembly, recycling, and remanufacturing, as well as the disposal of those materials and products that cannot be reprocessed and may be hazardous (Gungor & Gupta, 1999; Ilgin & Gupta, 2010; Kumar & Kumar, 2013). These and other related issues are explored within this dissertation, with a specific focus on the strategic planning and tactical planning levels of RSC management.

The purpose of this paper is to examine the issues that are related to strategic and planning levels of RSC, to enable cost-effective remanufacturing operations that reduce non-renewable resource utilization, and avoid premature disposal of functioning components and assemblies. A key side of such efforts is the development of RSC systems capable of facilitating a reverse flow of used products from consumers back to manufacturers, at which point they may be refurbished or remanufactured to realize both environmental and economic benefits. This particular side of the issue has been understudied in extant literature, and the in-depth consideration thereof is a key part of the empirical contribution of this paper. This paper develops novel and empirical multi-objective optimization model to inform RSC system design in the level of policy planning to account for potential valuation of RSC emissions. The work herein advances the theoretical modeling of optimal RSC systems while presenting an empirical case study of remanufactured appliances, an understudied facet of current industrial engineering literature.
The paper is organized in the following manner. In Section 2, literature review. In Section 3 the methodology that has been utilized in this study is presented. In Sections 4 and 5, nomenclature and problem formulation are explained. The energy survey databases that are used are presented in Section 6. In Sections 7 and 8 explain the numerical example and results and detailed results of the design of the study’s experiments, respectively. Finally, conclusions remarks and recommendations for future research are presented in Section 9.

2. Literature review

2.1. Circular economy and reverse supply chains for remanufacturing

A circular economy encourages the use of remanufacturing over other waste management strategies such as reusing, recycling, recovery, and disposal. A critical review of existing studies on remanufactured products using reverse logistics was done by Peters (2016). Recent research by Derigent and Thomas (2016) concerned product and material recyclable in the framework of a circular economy, including a review of the existing literature and highlighting potential research directions. Govindan and Soleimani (2016) did an extensive review of the literature on reverse supply chain issues. In general, an efficient reverse supply chain can reduce the overall cost of reverse logistics operations as well as the demand for new raw material in the chain.

In environmental terms, remanufactured products are highly sustainable and encourage both energy and resource saving; the procedures involved also create jobs for skilled workers (Charter & Gray, 2008). Ultimately, product remanufacturing process decisions must be integrated at an early stage in the product life cycle (Subramoniam, Huisingh, & Chinnam, 2009; Subramoniam, Huisingh, Chinnam, & Subramoniam, 2013) to guarantee these kinds of successful outcomes.

Considering carbon-constrained economy matters, replacing the original equipment manufacturer (OEM) with a remanufactured product would generate large revenue in terms of carbon-saving returns. Usually, OEM is in reference to the company that originally manufactured the product and/or used virgin materials. Many studies have confirmed, however, that remanufacturing is more profitable for OEMs (Hammond, Amezquita, & Bras, 1998; Guide, 2000).

An effective RSC can help enterprises better utilize their resources and maintain a more sustainable balance between economic concerns and the environment (Xiangru, 2008). RSC practices are additionally valuable towards ‘greening’ the entirety of the supply chain by inserting used and end-of-life products back into the system of production (Efendigil, Önüt, & Kongar, 2008). RSC efforts are widely considered to be a central component of sustainable development (Prakash & Barua, 2015).

Swift and effective resolutions in cases of defective products are now part and parcel of customer expectations: in some cases, the rate of product return is very high indeed, representing as much as 50% of the total sales (Senthil et al., 2014). While many products remain on a pathway that ends with the customer, there has been a clear increase in an alternative direction for products. The shift has been particularly noticeable in electronic items such as digital cameras, personal computers, and mobile phones, with other sectors like automobiles, beverages, and pharmaceuticals following
Changes in the supply chain have been incorporated within the automobile industry through the entire infrastructure of US vehicle recovery, building upon the recovery of end-of-life vehicles (Boon et al., 2000; Ferguson & Browne, 2001).

### 2.2. Greenhouse gas emissions and input-output life cycle assessment studies in reverse supply chains

Sustainable supply chain management has been defined by Seuring and Müller (2008) as the proactive management of the data, capital flows, and materials of the supply chain, in addition to cooperating efforts between companies throughout the supply chain, while incorporating the three dimensions of sustainable development, economic, social, and environmental, which are largely sourced through the requirements of both customers and stakeholders. Within this study, supply chain economics are exercised through the maximization of profitability in concert with the minimization of CO$_2$ emissions, rent, energy use, labor transportation, and the recovery costs of product recovery. This is achieved by considering the elements affecting costs in accordance with the type of facility, elements including on-site, inter-facility, and total tCO2e, further measuring the electrical use of individual units on-site. Regulations linked to Greenhouse Gas (GHG) emissions and environmental sustainability are serving to prevent substantial damage to the environment from occurring. Herein the social dimension explored is comprised of, but not limited to, a decrease in the detrimental consequences of noise, traffic congestion, coastal destruction, the prevalence of disease, stress, and an overall upward shift in the quality of life.

In Japan, at least 80% of the air conditioners material recycled under the home appliance recycling law which forces manufacturers to recycle. In 2014 by itself, Japan recovered about 230,000 products totaling of 10,783 tons, with a total of 89% recycling ratio (Daikin, 2015).

Meixell and Gargeya (2005) presented an extensive literature review on the economic facets of supply chain design, with an in-depth exploration of extant literature on the sustainable supply chain was conducted by Seuring and Müller (2008) and Srivastava (2007).

Further current reviews of literature concerning various facts of supply chain sustainability include: energy use (Dotoli, 2005), GHG emissions reduction (Guillen-Gosalbez & Grossmann, 2009), green design (Hugo & Pistikopoulos, 2005), product recovery (Jayaraman, 2006), production planning and control for remanufacturing (Hugo, Rutter, Pistikopoulos, Amorelli, & Zoia, 2005), reverse logistics (Sheu, 2008), and waste management (Guillen-Gosalbez & Grossmann, 2009).

Issues concerning environmentally conscious manufacturing and product recovery were explored by Gungor and Gupta (1999) in a thorough review of the literature. The researchers considered the product recovery process from the perspective of environmentally conscious manufacturing, and considered issues shared between environmentally conscious manufacturing and product recover, such as environmentally conscious design and production, inventory control, production planning, remanufacturing, and recycling. A literature review on the subject was brought up to 2010 by Ilgin and Gupta (2010). Further researchers have considered product recovery designs under the context of particular regulations and legislation (Bellmann & Khare, 2000; Das, 2002; Dekker,
The importance of decreasing the production emissions through the supply chain is an increasingly important goal. Due to such concerns, the factors considered in the supply chain have expanded beyond cost, service, and quality to include carbon output (Chaabane, Ramudhin, & Paquet, 2012). Paksoy, Bektaş, and Özceylan (2011) explored the concept of a ‘closed-loop supply chain’ (CLSC) network, considering the logistics related to transportation costs and GHG emissions, to consider the interrelationship of operational and environmental performance metrics. Carbon emission due to supply chain network design and supplier selection was explored by Abdallah et al. (2012), employing the life-cycle assessment approach.

Alkhayyal (2019) has done a research model for Corporate Social Responsibility Practices using the market price for greenhouse gas (GHG) emissions to illustrate how the policies, and economic and environmental implications of the carbon price can be formulated using a deterministic equilibrium model. It concludes that the costs associated with remanufacturing are linked not only to the economy but to the environment as well. Thus, the proximity of facilities to cities and centers of high reclamation and recycling levels is important to ensure not only that costs are minimized, but also the environmental impact of operations. Diabat and Simichi-Levi (2010) presented a mixed-integer programming model to identify an ideal strategy for organizations seeking to reach the carbon cap while at the same time keeping costs to a minimum. Alkhayyal, Gupta, and Eckelman (2016a, 2016b), likewise applied a mixed-integer linear programming model to identify the ideal flow of parts between multiple remanufacturing centers, seeking to minimize costs within the context of a particular carbon tax.

Chaabane et al. (2012) created a model that targeted processes with an aluminum firm, and explored the effect of carbon emissions on the design of a sustainable CLSC network rooted in the precepts of LCA; the study also considered the interplay between environmental and economic factors related to a costs and strategy. Diabat, Abdallah, Al-Refaie, Svetinovic, and Govindan (2013) considered the factors to consider concerning facility location in CLSC taking into account the trading price of carbon emissions and the cost of procurement. The impact of forward and reverse supply chain management on the carbon footprint was considered by Fahimnia, Sarkis, Dehghanian, Banihashemi, and Rahmanm. (2013) through the use of a mixed integer linear programming (MILP) model, in which carbon emissions are quantified by dollar carbon cost. Chaabane, Ramudhin, and Paquet (2011) developed a multi-objective mixed-integer linear programming model to determine the trade-off between economic and environmental considerations when designing a supply chain. The model considered carbon emissions, supplier and subcontractor selection, transportation mode, total logistics costs, and technology acquisition.

Benjaafar, Li, and Daskin (2013) measured the effect of carbon emissions in a strategy deploying lot sizing models into operational decisions, and the substantial reductions in emissions that can be realized without a rise in cost through just shifts in operational strategy. Jin, Granda-Marulanda, and Ian (2014) explored the supply chain and transportation mode selection of a major retailer in relation to their carbon policies.

Importantly, some research has applied the effect of incorporating international, national and corporate policies and legislations on a sustainable supply chain. For
example, Nagurney, Liu, and Woolley (2006) considered carbon taxes in the supply chains of electric power; Subramanian, Talbot, and Gupta (2010) proposed an approach to the decision-making level to add and integrate environmental consideration with their overall agenda. Thurston & Eckelman (2011) evaluated the GHG emissions for Yale University’s purchases of goods and services over a one-year period, to improve the university green supply chain management and to help in its efforts to reduce overall GHG emissions.

Biswas, Duong, Frey, and Islam (2013) compared the impact on the environment among repaired, remanufactured, and new air compressors. The results showed that a remanufactured air compressor generates 96% decrease in carbon emissions compared to the alternatives. Likewise, Zanghelini, Cherubini, Orsi, and Soares (2014), showed that the remanufacturing process saves 46% in carbon emissions compared to newly produced air compressor production systems.

Currently, there are a number of international, national and corporate policies intended for pollution reduction, in a flexible and economical manner, via emissions taxes. In this paper, the focus is on the social cost of carbon emitting a metric ton of carbon dioxide; the SC-CO$_2$ was designed by the US Environmental Protection Agency (EPA), together with other federal agencies, to estimate the climate benefits and legislative costs of meeting targets under the Kyoto Protocol.

That being said, the principal aim here is to compare the economic and environmental impacts on remanufactured air conditions in a reverse supply chain model. With the dramatic increase in the world’s consumption of household and industrial products, there has been an equivalent reaction to decrease the depletion of mineral resources, the volume of waste produced and the quantity of end-of-life products that are ultimately delivered to scrap yards.

This research model produces a full measurement of emissions to identify the ideal flow of parts among many remanufacturing facilities (thereby maximizing the net profit and minimizing CO$_2$ emissions) by investigating the cost factors and total tCO2e from actual sites in the Boston area (Alkhayyal & Gupta, 2018a). A direct carbon tax, determined in line with ranges presented in the 21st Climate Change Conference (COP21) in Paris by the US Environmental Protection Agency (US Environmental Protection Agency, 2015), and the US Interagency Working Group (Interagency Working Group, 2013) is used, to illustrate the way in which the policy presented will impact the profit margins of remanufactured goods. The data on consumption and expenditures are taken from the latest 2012 Commercial Buildings Energy Consumption Survey (CBECS) and the 2010 Manufacturing Energy Consumption Survey (MECS) databases (EIA, U.S, 2012, 2010), based on the New England census division; deterministic model is thus developed, and orthogonal array testing was included to allow for the full evaluation of all possible inputs to the systems.

3. Methodology

The methodology deployed is a mixed integer linear programming model of reverse supply chain including total valuation of emissions, exploring these factors to identify the ideal flow of parts between many remanufacturing facilities, presenting a strategy through which net profit may be optimized while CO$_2$
emissions, energy use, labor, product recovery, rent, and transportation costs are minimized.

Factors determining expenditure are investigated depending upon the facility type (on-site, inter-facility and total tCO2e) from on-site electricity utilization per unit, based upon real sites in the Boston Metropolitan region. The quantification of emissions is accomplished through the use of a direct carbon tax, the value of which varies according to the ranges presented at the 21st Climate Change Conference (COP21) in Paris by the US Interagency Working Group (Interagency Working Group, 2013) and the US Environmental Protection Agency (US Environmental Protection Agency, 2015): this will identify how the policy proposed will impact the profitability of remanufactured goods. The consumption and expenditures data are taken from the latest 2012 Commercial Buildings Energy Consumption Survey (CBECS) and the 2010 Manufacturing Energy Consumption Survey (MECS) databases (EIA, U.S, 2012, 2010), based on the New England census division. A deterministic and stochastic model is developed, and orthogonal array testing allows for full consideration of all possible inputs in each system.

3.1. Mixed integer linear programming approach

This approach is to optimize a linear objective function, subject to linear constraints. For example, the expression of a linear programming problem as:

Maximize $Z \ X$ (objective function)
Subject to $A \ X \leq B$ and $X \geq 0$ (constrains)

where $X$ represents the vector of variable, $Z$ and $B$ represent the vectors of coefficients and $A$ is the matrix of coefficients. When the variables of this linear problem are restricted to be integers, then the model is going to be called liner integer problem. Mixed-integer linear programming (MILP) is a special case, 0–1 integer linear programming that involves both constrained variables to be integers and non-integers. It is a very general and important context for solving problems with both discrete decisions and continuous variables. It can be applied to business, economic, and engineering problems.

4. Nomenclature

The nomenclature employed herein is presented below:

| Variables | Definition |
|-----------|------------|
| $O_1$     | Occupied space by remanufacturing unit; |
| $O_2$     | Occupied space by used-product unit; |
| $RCAP_v$  | Remanufacturing facility $v$ capacity; |
| $R_{ut}$  | Retrieval cost per unit at collection center $u$; |
| $SH_u$    | Shortage cost per unit at collection center $u$; |
| $H_u$     | Holding cost per unit at collection center $u$; |
| $D_w$     | Demand of products at reselling center $w$; |
Decision variable for the number of units transferring from collection center $u$ to remanufacturing facility $v$;

Decision variable for the number of units transferring from remanufacturing facility $v$ to reselling center $w$;

Reprocessing cost per unit at remanufacturing facility $v$;

Storage capacity at collection center $u$ per unit;

Storage capacity at remanufacturing facility $v$ per remanufactured unit;

Storage capacity at remanufacturing facility $v$ per used unit;

Storage capacity at reselling center $w$ per unit;

Supply at collection center $u$;

Transportation cost from collection center $u$ to remanufacturing facility $v$, per unit;

Transportation cost from remanufacturing facility $v$ to reselling facility $w$, per unit;

$CO_2$ emissions cause by transferring from collection center $u$ to remanufacturing facility $v$, in tons per mile;

$CO_2$ emissions cause by transferring from remanufacturing facility $v$ to reselling center $w$, in tons per mile;

$CO_2$ emissions factor of a remanufacturing facility $v$, in tons per ft$^3$;

$CO_2$ emissions factor of a remanufacturing facility $v$, in tons per KWh of operation;

Energy cost at collection center $u$ per unit;

Energy cost at remanufacturing facility $v$ per unit;

Energy cost at reselling center $w$ per unit;

Rent cost at collection center $u$ per unit;

Rent cost at remanufacturing facility $v$ per unit;

Rent cost at reselling center $w$ per unit;

Labor cost at collection center $u$ per unit;

Labor cost at remanufacturing facility $v$ per unit;

Labor cost at reselling center $w$ per unit;

Collection center;

Remanufacturing facility;

Reselling center;

Binary variable (0/1) for selection of remanufacturing facility $v$.

5. Problem formulation

Herein, the model employed was formulated as a single-period mixed integer linear programming model of reverse supply chain (Alkhayyal & Gupta, 2018a), in which the complete quantification of emissions is explored to identify the ideal flow of parts between multiple remanufacturing facilitate that has the potential to maximize total profitability while minimizing the $CO_2$ emissions, energy use, labor, product recovery costs, rent, and transportation.
Minimize

Retrieval cost \( \sum u \sum vR_uX_{uv} + \)

Transportation cost \( \sum u \sum vTX_uX_{uv} + \sum v \sum wTY_uY_{uv} + \)

Rемanufacturing cost \( \sum v \sum wP_vz_{vw} + \)

Inventory cost \( \sum u + \sum vR_u * X_{uv} + \sum v + \sum wP_v * Y_{uv} + \{(D_w - SUP_u) * (Z)\} * H_u + \)

Rent cost \( \sum u \sum RX_u + \sum v \sum RY_v + \sum w \sum RZ_w + \)

Labor cost \( \sum u \sum LX_u + \sum v \sum LY_v + \sum w \sum LZ_w + \)

Energy cost \( \sum u \sum EX_u + \sum v \sum EY_v + \sum w \sum EZ_w + \)

CO2 emissions \( \sum u \sum vCX_uX_{uv} + \sum v \sum wCX_vX_{vw} + \sum CY + \sum CZ + \)

Shortage cost \( \{(D_w - SUP_u) * (1 - Z)\} * SH_u \)

Subject to

Demand constraint must be reached while the total cost of production and inventory is minimized.

\( \sum v Y_{vw} \geq D_w; \ \forall \ w \) (2)

The remanufacturing facility total output is at greatest the total input thereof

\( \sum u X_{uv} \geq \sum w Y_{vw}; \ \forall \ v \) (3)

The space occupied at each remanufacturing facility by remanufacturing items is at the greatest the capacity thereof, and the total space occupied by returned items at each collection center is at most its capacity

\( \sum w O_{1v}Y_{vw} \leq C_{1v}, \ Y_{v}; \ \forall \ v \) (4)

\( \sum u O_{2v}X_{uv} \leq C_{2v}, \ Y_{v}; \ \forall \ v, \) (5)

The total space utilized at each remanufacturing facility by returned items is at greater the capacity of the facility

\( \sum v O_{2u}X_{uv} \leq C_u; \ \forall \ u \) (6)

The total space utilized at each reselling center by returned items is at the greatest its capacity

\( \sum v O_{1w}Y_{uv} \leq C_w, \ Y_{w}; \ \forall \ w \) (7)

Non-negativity constraint

\( X_{uv} \geq 0; \ \forall \ u, v \) (8)
\[ Y_{uv} \geq 0; \quad \forall \ w, v \]  
(9)

The total quantity of returned items supplied to remanufacturing facilities from collection centers is at maximum the supply

\[ \sum_w Y_{wv} \leq RCAP_v; \quad \forall \ v \]  
(10)

\[ \sum_v X_{wv} \leq SUP_u; \quad \forall \ u \]  
(11)

6. Data

This section employs two differing survey databases, CBECS in subsection 6.1. was for the energy data of collection and reselling centers. MECS was utilized for the energy data of remanufacturing facilities in subsection 6.2.

6.1. Commercial buildings energy consumption survey (CBECS)

CBECS is a survey conducted nationally that gathers data on commercial buildings, including their characteristics linked to energy and data concerning energy use (consumption and expenses). The term commercial buildings comprises all buildings in which a minimum of half of the available floor space is deployed for a use that is not agricultural, industrial, or residential. The latest survey was conducted in 2012, and the microdata file contains 6,720 records for building characteristics in the USA (EIA, U.S, 2012)

![Electricity Usage-CBECs](image)

Figure 1. Shows the space heating demanded the most overall energy use in commercial building, followed by other uses.
Our model used the following criteria from the survey, as shown in Figures 1 and 2:
Principal building activity: Retail (other than mall)
Census region and division: New England
Establishment counts, total floor-space per establishment, cooling, space-heating, ventilation, lighting, refrigeration, water heating, cooking, office equipment, computers, and others. This helps in classify our commercial buildings fixed and variable cost and usage. Most of their usages are electricity and natural gas. CBECs data were used in identifying the collection centers and the reselling centers in our numerical example.

6.2. Manufacturing energy consumption survey (MECS)

MECS is a sample survey conducted nationally that gathers data on manufacturing establishments, their building characteristics linked to energy and their energy consumption and expenses. The MECS was first engaged in during 1985, the most recent survey conducted was in 2010; the first data set was made available in February 2013. MECS is conducted on a quadrennial basis currently and uses the North American Industry Classification System (NAICS) to classify business establishments based upon the sort of economic activity (process of production) in Canada, Mexico and the USA (EIA, U.S, 2010).

Our model used the following criteria from this survey, as shown in Figures 3 and 4:

NAICS Code: 335
Subsector and Industry: Electrical Equip., Appliances, and Components
Census region and division: New England
Establishments counts, total floor-space per establishment, process cooling and heating, refrigeration, facility HVAC, machine drive, and facility lighting.

Most of their usages are electricity and natural gas. Distillate fuel oil and diesel, and residual fuel oil are less than 0.5 million bbl. MECS data were used in identifying the remanufacturing facilities in our numerical example.

Figure 3. Shows the machine drive demanded the most overall energy use in remanufacturing facilities, followed by other uses.

Figure 4. Shows natural gas accounts for 41% of all energy consumed in remanufacturing facilities.
Figure 5. The actual sites in the Boston, Massachusetts area.
7. Numerical example

Herein the numerical model example is rooted in real sites in the Boston Metropolitan region, and considers the situation of three particular collection centers located in Canton, Melrose, and Natick, two remanufacturing facilities situated in Hingham and Taunton, and three centers of reselling situated in Boston, Revere, and Somerville, as exhibited in Figure 5. The actual distances between the locations were explored by mile to determine the mile-per-gallon expenditures alongside emissions of CO₂ kg per gallon, applying the per-gallon price of gasoline from October 2015. The quantity of laborers alongside their annual salary, in addition to the size of the space were also factored into consideration. In summary, the example presents the breakdown of cost factors – CO₂ emissions, energy, labor, rent, and transportation – by the type of facility; (inter-facility, on-site, and total tCO₂e) from on-site electricity utilization by unit. U.S. Energy Information Administration at the US Department of Energy data reports (U.S. Energy Information Administration, 2015) was employed to quantify the energy usage within the facilities explored. This example explores a mid-sized LG A/C unit model LW1213ER with measurements of 23 5/8” × 15” × 22 1/6”, with a market price for the refurbished product being $288 (LG Model: LW1213ER, 2016) Two 12 ft. trucks with a load volume of 475 cubic feet were utilized for transportation which have a capacity equivalent to 58 A/C units each (12 Foot Truck, 2015). The valuation of emission was accomplished through the use of a direct carbon tax, with the value varying in accordance with ranges proposed at the COP21 climate talks in Paris, by the conjoined efforts of the US Interagency Working Group (2013) and the US Environmental Protection Agency (2015) to identify the ways in which the policy proposed will affect the profitability and margins of remanufactured goods. Table 1 shows the collection centers data that we collected from each collection center; however, appendix I has all rent and labor costs, and trip distances between locations. Deterministic model is thus developed, and orthogonal array testing was included to allow for the full evaluation of all possible inputs to the systems.

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

8. Results

In this section the results of deterministic model are explained in subsection 8.1., the results of the effect of different social cost of carbon and demand are in subsection 8.2., and design of experiments to study the effect of the cost factors in subsection 8.3.
8.1. Deterministic model

Without the presence of a carbon tax, the A/C unit’s profit margin is 26%, while a USEPA-recommended $40/ton CO$_2$ equivalent (tCO$_2$e) tax results in a decrease in the profit margin to 19% (US Environmental Protection Agency, 2015). LINGO 13.0 was utilized to identify a solution to the problem. The results produced are exhibited in Figure 6. The remanufacturing cost is $107,002 ($233 per unit), demonstrating that our model is $55 per unit less than the market price currently in place for the refurbished product (LG Model: LW1213ER Refurbished, 2015). The emission volume relative to this solution is 0.07 tCO$_2$e per unit. Contrasting the result we generated to deflated refurbished market prices through the use of consumer price index expressed in 2002 dollars (BLS, 2010), and considering that result through the utilization of the economic input-output life cycle assessment (EIO-LCA) model, which is a strategy through which the materials and energy resources required for environmental emissions resulting from the various activities of our economy are estimated (Carnegie Mellon University Green Design Institute, 2016). The sector of EIO-LCA that was chosen as the US 2002 Benchmark for air conditioning, refrigeration, and warm air heating equipment manufacturing, which demonstrates that
our emission volumes are 0.03 tCO$_2$e per unit lower than refurbished manufacturing. Figure 7 shows the effects of the social cost of carbon on unit price by comparing our remanufacturing model and the EIO-LCA manufacturing model, on a range of proposed SCC by a recent U.S. government study with $220 per ton as studied by Moore and Diaz (2015). Therefore, existing approaches used are as a result of different carbon policies.

8.2. Effect analysis

The computer model we deployed utilized a median estimate of the social cost of carbon at $40/ton but allows for the true social cost of carbon (SCC) to be positioned anywhere in the range of $0/ton to $120/ton with a confidence level of 95%. Consider once more the example presented above, in which the estimate of the point was $40/ton while the lower bound was $0/ton. Figure 5 shows the effect of different SCC on unit price, and it is noted from the graph that the apparent unit price of the estimate increases considerably as the estimate nears $66/ton and above. This piecewise linear has three different segments as shown below in Figure 5, and each segment has successive pair of points are connected with a straight line.

Moreover, the model allowed the estimate of demand number of units could fall anywhere in the range of 70 to 1000 as collected from the collection centers in our example above. It is apparent in the chart in Figure 6 that the apparent unit price of the demands increases considerably as the demand nears the lower bound of 70 units. Also, the unit price gets lower with high demands.

8.3. Design of experiments study

The research herein was conducted to study the effect of the different cost factors by using an orthogonal array and regression analysis.
8.3.1. Orthogonal array

Comprehensive research to determine the quantitative evaluation and the performance of the model has been done. A full-factorial design with 13 factors requires a significant number of experiments (viz., 1.59E+4). Thus, experiments were designed through the use of Orthogonal Arrays (OA) which allows for full testing of every possible input to the systems by producing a minimum quantity of experiments. L_{27} OA was utilized, which requires 27 experiments while satisfying 13 factors with three different levels that each one of them has a physical meaning which mimics the real-life example. Table 2 has the factors and factor levels that were utilized in the experiments, and Appendix II L_{27} OA with 27 experiments. The 27 experiments table results are in Appendix III.

### Table 2. Factors and factor levels employed in design-of-experiments study.

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

### Table 3. Analysis of variance output summary.

| Source                | DF | Adj SS   | Adj MS | F-value | p-value |
|-----------------------|----|----------|--------|---------|---------|
| Regression            | 5  | 51693047199 | 10338609440 | 29.94 | 0.000  |
| Transportation Cost   | 1  | 28251228988 | 28251228988 | 81.82 | 0.000  |
| Remanufacturing Cost  | 1  | 5852940984  | 5852940984  | 16.95 | 0.000  |
| Retrieval Cost        | 1  | 3645189436  | 3645189436  | 10.56 | 0.004  |
| Inventory Level       | 1  | 891788427   | 891788427   | 2.58  | 0.123  |
| Supply Rate           | 1  | 3896876283  | 3896876283  | 11.29 | 0.003  |
| Error                 | 21 | 7250950684  | 345283366   |        |        |
| Total                 | 26 | 58943997883 |        |        |        |
| R-squared             |    |           |         | 87.70% |        |

### Table 4. Regression analysis output summary.

| Factors          | Estimate | Std. Error | t-value | p-value |
|------------------|----------|------------|---------|---------|
| Constant         | -39,134  | 17,882     | -2.19   | 0.040   |
| Transportation Cost | 79,234   | 8760       | 9.05    | 0.000   |
| Remanufacturing Cost | -2592    | 629        | -4.12   | 0.000   |
| Retrieval Cost   | 1897     | 584        | 3.25    | 0.004   |
| Inventory Level  | 5.65     | 3.52       | 1.61    | 0.123   |
| Supply Rate      | 17.96    | 5.35       | 3.36    | 0.003   |
| R-squared        |          |            |         | 87.70%  |
8.3.2. Regression analysis

An estimating linear regression model using MINITAB 17 was performed, to examine the factors which the statistical analysis tells us are effect the total cost. Tables 3 and 4 show the output summary using Stepwise Selection feature, which is the systematic process that adds the most substantial variable or removes the least substantial variable within each step. The analyses only consider those factors that were found to be significant. Any factor mentioned in Table 2 but not mentioned here was tested and found insignificant. The R-square value indicates that 87.70% of the variation in the total cost is explained by the linear fitted model. Figure 7 demonstrates the residuals plotted in contrast to the predicted values. It seems that the residuals show an ideal random scatter around a value of zero. This indicates that the residuals are homogenous.

To establish a basic understanding of the concepts pertaining to the normal error assumption, a normal probability plot of the residuals was produced and shown in Figure 8. The normal probability plot shows that the residuals strongly support the normality assumption.

9. Conclusion & recommendations for future research

This research has put forth an optimization model for a reverse supply chain positioned to understand and quantify the impact of both operational and strategic activities of the supply chain upon the environment. The climate change concerns are continuing to increase along with the acceleration of global warming. The IPCC reports that globally GHG emissions have increased by more than 80% from 1970 to 2010, resulting in widespread threats to global ecosystems and human enterprise (IPCC, 2014). The new Paris agreement proposes a means to achieve zero net GHG emissions by the second half of this century (Conference of the Parties (COP21), 2015). The current model introduced with potential increases in carbon costs, the optimal RSC system is likely to differ with respect to how be effectively managed and minimized. Results from the model have been studied comprehensively in terms of quantitative performance using Orthogonal Arrays. The results were compared to top-down estimates from economic input-output life cycle assessment (EIO-LCA) models, to provide a basis to contrast
remanufacturing GHG emission quantities with those realized through original equipment manufacturing operations. Introduction of a carbon cost of $40/t CO2e increases modeled remanufacturing costs by 2.7% but also increases original equipment costs by 2.3%. The work herein advances the theoretical modeling of optimal RSC systems while presenting an empirical case study of remanufactured appliances, an understudied facet of current industrial engineering literature. A numerical example rooted in real sites was explored to examine the model’s performance and to identify how the policy proposed would impact the profit margins of remanufactured goods. The results demonstrate that the current carbon tax policy will not bring about a strict limitation on the volume of carbon emissions that are produced through supply chain operations.

The work contained in this paper can be extended in a number of ways. An important side of current research that is relevant to the entire paper is the increasing use of embedded sensors in used products under the concept of the Internet of Things (IoT) and the increasing availability of high-resolution data. Embedded sensors can provide information related to use, transportation, repair, and remaining service life of products, whether new or used. New types of data coming from product sensors, such as transit time or records of product energy use, could be integrated in the generic model developed. Embedded sensors could also be used to further calibrate the RSC case study presented, for example, by tagging all products coming through a certain remanufacturing center and extracting trip-related information. Diagnostic data represents another potentially beneficial data stream from embedded sensors for remanufacturing operations that will inform repair decisions, disassembly for specific components, and overall economic benefits of remanufacturing.

A number of model extensions and refinements could be made. First, the deterministic model could be relaxed to facilitate the potential to relocate remanufacturing facilities/reselling centers rather than shutting down the facility, based upon factors such as traffic congestion and parking difficulties; commuting distance; current land/energy/labor cost criteria; and general population, economy, and geographic characteristics of the setting. Proximity of additional recycling infrastructure, such as rail lines, Material Recovery Facilities, shipping terminals, and disposal facilities, and their incorporation in a spatially explicit RSC may serve to make the models presented here more realistic. The case study used both facility-specific operational data as well as energy use estimates from CBECS. The case study could be made even more representative by obtaining metered energy data from those facilities, as well as actual logs of inventory trucked among the different RSC facilities. Finally, the used variable social cost of carbon whose value was set to levels recommended by government agencies and reports to represent a carbon tax on all activities leading to GHG emissions. Other policy means of controlling GHG emissions such as strict carbon caps or cap-and-trade policies have been modeled in industrial engineering literature and could be considered here, which would require problem reformulation. The existing cost model could also be used to determine how much GHG emissions are reduced by remanufacturing versus disposal, providing a value for the cost of carbon abatement from remanufacturing operations that could be of use to environmental economics research.
Disclosure statement

No potential conflict of interest was reported by the author.

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