Carbon Emissions Policies Impact On Reverse Supply Chain Network

Bandar A. Alkhayyal
Department of Engineering Management
College of Engineering
Prince Sultan University
Riyadh, Saudi Arabia
balkhayyal@psu.edu.sa

Abstract

Reverse Supply Chain is described as an initiative that plays an important role in the global supply chain for those who seek environmentally responsible solutions for their end-of-life products. The relative economic and environmental benefits of reverse supply chain are influenced by costs and emissions during collection, transportation, recovery facilities, disassembly, recycling, remanufacturing, and disposal of unrecoverable components. The design of reverse supply chain network takes into account social, economic and environmental objectives. This research addresses the design of reverse supply chain that is also sensitive to the carbon policies under the three common regulatory policies, strict carbon caps, carbon tax, and carbon cap-and-trade. CO2 emissions and total profit are integrated using a multi-criteria decision making model. In this research, a mixed integer linear programming model of reverse supply chain with full valuation of emissions is considered to determine the optimal flow of parts among multiple remanufacturing centers that will maximize the total profit with less CO2 emissions, based on actual sites in the Boston area. Numerical example illustrates different policies and their impact on the costs and the effectiveness of emission reduction.

Keywords

Greenhouse gas (GHG) emissions, low carbon logistics, reverse supply chain, sustainably supply chain, supply chain engineering

1. Introduction and Related Work

The number of products discarded by consumers has been gradually growing, which has led to legislations in various countries that hold the original equipment manufacturers (OEM) responsible for the end-of-life processing of products. In addition, the field of supply chain has also been influenced by consumer awareness of environmental issues (Vadde, Kamarthi, & Gupta, 2006) & (Ilgin & Gupta, 2010).

Climate change, disposal capacities, finite resources, growing population, improving quality of life, increasing emissions, and rising energy prices have motivated both corporations and academics to develop strategies based on corporate social responsibilities and sustainable supply chains (Carter, 2008), (Nagurney, Zugang, & Trisha, 2007), & (Paul, Kalyan, & Luk, 2005). While the concept of integrating sustainability into supply chain is relatively new, its implementation is however increasing continuously (Seuring, Joseph, Martin, & Purba, 2008).

Nowadays, although the products are still moving in the direction of the end customer the reverse flow of products is also taking place. This movement is obviously pronounced in most of the industrial sectors, especially in automobiles, beverages, electronic products, and pharmaceuticals. The automobile industry, for example, has included the changes in the supply chain to smooth the end-of-life vehicles recovery and the US vehicle recycling infrastructure (Boon, Isaacs, & Gupta, 2000) & (Ferguson & Browne, 2001).

Reverse Supply Chain (RSC) is an initiative that plays an important role in the global supply chain for those who seek environmentally responsible solutions for their end-of-life (EOL) products. The relative economic and environmental benefits of RSC are influenced by costs and emissions during collection, transportation, recovery facilities, disassembly, recycling, remanufacturing, and disposal of unrecoverable components (Ilgin & Gupta, 2010) , (Alkhayyal & Gupta, 2015), and (Gupta, 2013).

Seuring and Muller (2008) defined the sustainable supply chain management as "the management of materials, information and capital flows as well as cooperation among companies along the supply chain while taking goals from all three dimensions of sustainable development, viz., economic, environmental and social, into account which are derived from customer and stakeholder requirements". In this paper, the supply chain economics is taken into account by maximizing the total profit and minimizing the CO_2 emissions, energy use, transportation, rent, labor, and product recovery costs, by investigating the cost factors by facility type, on-site, inter-facility, and total tCO2e from on-site electricity use by unit. Greenhouse Gas (GHG) emissions regulations and environmental sustainability are preventing extreme environmental damages from happening. The social dimension includes, but not limited to, the reduction in negative consequences of coastal destruction, noise, stress, traffic congestion, spread of disease, and the improvement in the quality of life.

A literature review is conducted by Mexiell and Gargeya (2005) on economic considerations of supply chain design. A comprehensive review of the published literature on sustainable supply chain is presented by Seuring and Muller (2008), and Srivastava (2013).

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

Gungor and Gupta (1999) addressed the issues of environmentally conscious manufacturing and product recovery with an extensive review of the literature. The study looked at the product recovery process from environmentally conscious manufacturing point of view, and included the common issues in both environmentally conscious manufacturing and product recovery (viz. environmentally conscious design, environmentally conscious production, recycling and remanufacturing, and production planning and inventory control). Ilgin and Gupta (2010) further extended this literature review through 2010. There are several other authors who reported on product recovery designs under certain legislation and regulations (Das, 2002), (Bellmann & Khare, 2000), (Dekker & Fleischmann, 2004), (Fleishmann, 2000), (Guide, V. D. R., Jayaraman, V., & Srivastava, 1999), (Guide, 2000), & (Henshaw, 1994).

Reducing the emissions generated due to a supply chain has become an important goal. Thus, the "trade-offs in the supply chain are no longer just about cost, service and quality, but also about cost, service, quality and carbon," (Chaabane, Ramudhin, & Paquet, 2012). A Closed-loop supply chain (CLSC) network considered by Paksoy, Bektaş, & Özceylan (2011), focused on the transportation logistics cost and their GHG emissions, to exam the trade-off between operational and environmental performance measures. Abdallah, Farhat, Diabat, & Kennedy (2012) investigated the carbon emissions as a consequence of the supply chain network design and supplier selection using life-cycle assessment (LCA) approach.

A mixed-integer programming model was formulated to find an optimal strategy for companies to meet their carbon cap, while minimizing costs by Diabat and Simichi-Levi (2010). Chaabane, Ramudhin, & Paquet (2012) formulated a model of an aluminium firm and examined the carbon emissions impact on designing a sustainable CLSC network based on LCA principles. They also evaluated the tradeoffs between economic and environmental dimensions under various cost and strategies. The issues of facility location problem in CLSC with a trading price of carbon emissions and a cost of procurement were considered in Diabat et al.'s (2013) work. Fahimnia et al. ((2013) evaluated the forward and reverse supply chain influences on the carbon footprint using mixed integer linear programming (MILP) model, where carbon emissions are demonstrated in terms of dollar carbon cost.

Benjaafar, Li, & Daskin (2013) illustrated the impact of carbon emission and introduced a series of lot sizing models to be integrated into operations decisions and showed how significant emissions reductions without increases in costs can be achieved by operational adjustments alone. Supply chain and transportation mode selection decisions study for a major retailer based on the carbon policies was reported by (Jin, Granda-Marulanda, & Ian, 2014)

In this research, a mixed integer linear programming model of reverse supply chain with full valuation of emissions is considered to determine the optimal flow of parts among multiple remanufacturing centers that will maximize the total profit with less CO_2 emissions, based on actual sites in the Boston area. The proposed model considers a mid-sized LG A/C unit with a refurbished market price of $288 (LG Model: LW1213ER Refurbished, 2015). Valuation of emissions is done using a direct carbon tax, with the value varied according to ranges proposed at the current COP21 climate talks in Paris, and with the other two different regulatory policies, strict carbon cap where firms are subject to mandatory caps on the amount of carbon they emit, and carbon cap-and-trade where firms are subjected to carbon caps but are rewarded (penalized) for emitting less (more) than their caps. To that end, we determine how the proposed policies will influence profit margins for remanufactured goods.

The model proposed can be used for designing and analyzing a reverse supply chain in a carbon trading environment, and optimize not only costs but also emissions in the supply chain operations. It captures the trade-offs between costs and emissions in the supply chain operations. It shows that carbon tax emissions, particularly at higher taxes, mostly affects transportation operations which results in reduced transportation costs and emissions; on the other hand, the higher the carbon tax is, the greener would be the supply chain design, not necessarily following a linear relationship. Applying an emissions cap combined with a carbon tax slightly increases total supply chain costs, but yields a greener design. Numerical example illustrates different policies and their impact on the costs and the effectiveness of emission reduction.

2. Notation and Assumptions

2.1. Notation

The notations used in this paper are given below:

Notation	**Definition**
C1v	Storage capacity at remanufacturing facility *v* per remanufactured unit;
C2v	Storage capacity at remanufacturing facility *v* per used unit;
Cu	Storage capacity at collection center *u* per unit;
Cw	Storage capacity at reselling center *w* per unit;
CAP	Carbon strict cap;
Du	Demand of products at collection center *u*;
Dw	Demand of products at reselling center *w*;
duu	Distance from collection center *u* to remanufacturing facility *v*, per mile;
dwv	Distance from remanufacturing facility *v* to reselling center *w*, per mile;
EXu	Energy cost at collection center *u* per unit;
EXv	Energy cost at remanufacturing facility *v* per unit;
EXw	Energy cost at reselling center *w* per unit;
GH	GHG emissions per ton-mile;
GHu	GHG emissions in collection center *u*, per unit;
GHv	GHG emissions in remanufacturing facility *v*, per unit;
GHw	GHG emissions in reselling center *w*, per unit;
GHGt	GHG emissions total;
Hu	Holding cost per unit at collection center *u*;
Lu	Labor cost at collection center *u* per unit;
Lv	Labor cost at remanufacturing facility *v* per unit;
Lw	Labor cost at reselling center *w* per unit;
O_1	Occupied space by remanufacturing unit;
O_2	Occupied space by used-product unit;
Kg	Weight of each unit;
P	Reprocessing cost per unit;
R	Retrival cost per unit;
RCAPv	Remanufacturing facility *v* capacity;
RCu	Rent cost at collection center *u* per unit;
RCv	Rent cost at remanufacturing facility *v* per unit;
RCw	Rent cost at reselling center *w* per unit;
SHu	Shortage cost per unit at collection center *u*;
SUPu	Supply at collection center *u*;
Tuv	Transportation cost from collection center *u* to remanufacturing facility *v*, per unit;
Tvw	Transportation cost from remanufacturing facility *v* to reselling facility *w*, per unit;
u	Collection center;
v	Remanufacturing facility;

w	Reselling center;
Xuv	Decision variable for the number of units transferring from collection center *u* to remanufacturing facility *v*;
Yvw	Decision variable for the number of units transferring from remanufacturing facility *v* to reselling center *w*;
Zv	Binary variable (0/1) for selection of remanufacturing facility *v;*
Zw	Binary variable (0/1) for selection of reselling center *w.*

2.2. Assumptions

We assume that GHG emissions come from four sources:

1. from the collection centers: the amount of emissions is proportional to the power consumption of these centers;
2. from the remanufacturing facilities: the amount of emissions is proportional to the volume of these remanufacturing facilities;
3. from the reselling centers: the amount of emissions is proportional to the power consumption of these centers; and
4. from the distribution of the products: the emissions level is based on the traveled distance between facilities, and the weight of each unit (40 Kg).

The model also assumes that inventory cost of a used product at the remanufacturing facility is 25% of its retrieval cost (*R*), and for a remanufactured product it is 25% of its reprocessing cost (*P*).

3. Problem Formulation

The model is formulated as a single period mixed integer linear programming model of reverse supply chain where full valuation of emissions is considered to determine the optimal flow of parts among multiple remanufacturing facilities that will maximize the total profit which includes the CO_2 emissions, energy use, transportation, rent, labor, and product recovery costs.

Objective Functions

Minimize

$$\text{Retrieval cost } \sum_{u}\sum_{v} R \quad X_{uv} +$$

$$\text{Transportation cost } \sum_{u}\sum_{v} T_{uv} X_{uv} + \sum_{v}\sum_{w} T_{vw} Y_{vw} +$$

$$\text{Remanufacturing cost } \sum_{v}\sum_{w} P \quad Y_{vw} +$$

$$\text{Inventory cost } \sum_{u}\sum_{v} (R_{u}/4) X_{uv} + \sum_{v}\sum_{w} (Pv/4) Y_{vw} +$$

$$\text{Rent cost } \sum_{u} RCu * Du + \sum_{v} RCv * Xuv + \sum_{w} RCw * Yvw +$$

$$\text{Labor cost } \sum_{u} Lu * Du + \sum_{v} Lv * Xuv + \sum_{w} Lw * Yvw +$$

$$\text{Energy cost } \sum_{u} Eu * Du + \sum_{v} Ev * Xuv + \sum_{w} Ew * Yvw +$$

Greenhouse Gas (GHG) Emissions

$$\sum_u GHu * Du + \sum_u \sum_v GHvXuv + \sum_v \sum_w GHwYvw + \sum_u \sum_v GH * duv * Kg * Xuv + \sum_v \sum_w GH * dwv * Kg * Yvw$$

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

Constraints

Demand constraint must be met while minimizing the total cost of production and inventory.

$$\sum_v Yvw = D_w \; ; \; \forall w$$

Remanufacturing facility total output is at most its total input

$$\sum_u Xuv \geq \sum_v Yvw \; ; \; \forall v$$

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

$$\sum_w O_1 * Yvw \leq C_{1v} * Yv; \forall v$$

$$\sum_v O_2 * Xuv \leq C_u; \forall u$$

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

$$\sum_u O_2 * Xuv \leq C_{2v} * Zv; \forall v$$

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

$$\sum_v O_1 * Yvw \leq C_w * Zw; \forall w$$

Carbon strict cap limit

$$GHGt \leq CAP$$

Non-negativity constraint

$$X_{uv} \geq 0 \; ; \; \forall u, v$$
$$Y_{uv} \geq 0 \; ; \; \forall v, w$$

Total number of returned items supplied to remanufacturing facilities by collection centers is at most the supply

$$\sum_w Yvw \leq RCAPv; \forall v$$

$$\sum_v Xuv \leq SUPu; \forall u$$

4. Case Study

The numerical example is based on actual sites in the Boston (Massachusetts) area and considers three collection centers (located in Melrose, Canton, and Natick), two remanufacturing facilities (located in Taunton and Hingham), and three reselling centers (located in Revere, Boston, and Somerville). The actual distances in miles between the locations were considered, to calculate mile per gallon costs and emissions of CO_2 kg per gallon, assuming the gasoline price per gallon of October 2015. The number of laborers, their annual salaries, and the size of the space were also considered. In short, the example reflects a breakdown of the cost factors: rent, labor, energy, CO_2 emissions, and transportation, by facility type, on-site, inter-facility, and total tCO_2e from on-site electricity use by unit. The U.S. Energy Information Administration at the U.S. Department of Energy data reports (U.S. Energy

Information Administration, 2015) were used to calculate the energy usage for each facility. This example considers a mid-size LG A/C unit, model LW1213ER, with dimensions of 23 5/8" x 15" x 22 1/6", and a refurbished market price of $288 (LG Model: LW1213ER Refurbished, 2015). Two 12-foot trucks with a capacity of 58 A/C units each and a load volume of 475 cubic feet were used for transportation (12 Foot Truck, 2017). Valuation of emissions is done using the suggested direct carbon tax, strict cap, and cap-and trade values according to ranges proposed at the 21st Conference of the Parties under the UNFCCC in Paris (Conference of the Parties (COP21), 2015), the U.S. Interagency Working Group (2013) and, the U.S. Environmental Protection Agency (2015), to determine how proposed ranges will influence profit margins for remanufactured goods.

4.1. Data

In this section two different survey databases were used, Commercial Buildings Energy Consumption Survey (CBECS) which was used for collection centers and reselling centers energy data. Manufacturing Energy Consumption Survey (MECS) was used for remanufacturing facilities energy data in subsection. Tables 1 to 4 have the labor cost, rent cost, and distances between locations per mile respectively.

Table 1: Labor Actual Cost

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

Table 2: Rent Actual Cost

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

Table 3: Actual Distances between Collection Center and Remanufacturing Facilities per Mile

From/To City	Taunton	Hingham
Melrose	52.8	28.1
Canton	17.2	19.3
Natick	37.0	30.5

Table 4: Actual Distances Between and Remanufacturing Facilities and Reselling Centers per Mile

From/To City	Revere	Boston	Somerville
Taunton	45.0	40.0	43.0
Hingham	24.0	19.0	22.0

5. Results and Discussion

The absence of a carbon tax for the A/C unit priced at $218 results in a profit margin estimated to be 24.3% for a $288 selling price according to current refurbished market price (LG Model: LW1213ER Refurbished, 2015), whereas a USEPA-recommended $40/ton CO_2 equivalent (tCO2e) tax reduced the profit margin to 19.1% assuming a price for remanufactured item of $233 per unit (US Environmental Protection Agency, 2015). However, strict carbon cap reduces the profit margin to 13%, and cap-and-trade policy reduces the profit margin to 9%. LINGO 13.0 was used to solve the problem. The optimal results obtained from the direct carbon tax are shown in Tables 5 and 6.

Table 5: Optimal Number of Units Transported From Collection Center to Remanufacturing Facility

City	Taunton	Hingham
Melrose	0	50
Canton	0	0
Natick	0	450

Table 6: Optimal Number of Units Transported From Remanufacturing Facility to Reselling Center

City	Revere	Boston	Somerville
Taunton	0	0	0
Hingham	150	200	150

The optimal remanufacturing cost is $218 per unit, which shows that this model is $70 per unit less than the current refurbished market price. The emission quantity is 0.018 tCO2e per unit. Comparing this result to the deflated refurbished market price using a consumer price index expressed in 2002 dollars and analyzing that result using the economic input-output life cycle assessment (EIO-LCA) model a technique for estimating the materials and energy resources required for environmental emissions resulting from economic activities (Carnegie Mellon University Green Design Institute, 2016). The EIO-LCA sector chosen was the U.S. 2002 Benchmark for air conditioning, refrigeration, and warm air heating equipment manufacturing. This shows that the emission quantities are 0.109 tCO2e per unit less than refurbished manufacturing. The valuation of emissions for the optimal result was done by using the values according to ranges proposed at the 21st Climate Change Conference (COP21) in Paris, therefore existing approaches used different carbon policies and applications. Using the carbon price of $40/ton CO2 equivalent (tCO2e), our model gives a profit margin of 19.1%.

6. Conclusion

This paper has presented a reverse supply chain optimization model designed to take into account the influence of both strategic and operational activities of the supply chain on the environment. A case study based on actual sites was considered to illustrate performance of the model and to determine how the proposed policies would influence profit margins on remanufactured goods. The results indicated that the carbon price ranges that were used in this study will control the amount of GHG emissions generated in reverse supply chain operations. The results also indicated that the carbon tax policy forces a strict constraint on the amount of carbon emissions generated in supply chain operations. It shows that the RSC is sensitive to the carbon price. 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 literature.

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Biography

Bandar A. Alkhayyal is an Assistant Professor at the Department of Engineering Management in the College of Engineering at Prince Sultan University, Riyadh, Saudi Arabia. Dr. Alkhayyal received his B.S. degree in Computer Science with minor in Industrial Engineering from the Eastern Michigan University, Ypsilanti, Michigan, USA, in June 2010. In December 2011, he received his M.S. degree in Engineering Management specialized in Project Management from the same school in Michigan, and in May 2013 he received his M.S. degree in Industrial Engineering from New Mexico State University, Las Cruces, New Mexico, USA, and then he earned his PhD degree in Industrial Engineering from Northeastern University, Boston, USA on December 2016. Dr. Alkhayyal has certifications in Lean Six Sigma Green Belt, Lean Enterprise Systems, and Lean Concepts and Applications. His research interests are in the areas of environmentally conscious manufacturing, product recovery, reverse logistics, closed-loop supply chains (CLSC), sustainable operations and sustainability, modeling with applications in CLSC and multiple lifecycle products, environmental engineering and sustainability, life cycle assessment, energy efficiency and emissions modeling. He has co-authored several technical papers published in journals and presented at various national and international conferences.