Managing environmental issues in reverse supply chain

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Abstract

This research uses a multi-criteria decision making technique to address the situation of a reverse supply chain network with environmental concerns that captures the trade-off between profit and ecology goals. It determines the optimal flow of parts to maximize the total profit and minimize the CO2 emissions, energy, transportation, rent, labor, and product recovery costs. A mixed integer linear programming model is employed to facilitate the process. A numerical example is considered to illustrate the application of the model.

Keywords: *Low Carbon Logistics; Reverse Supply Chains; Sustainably Supply Chain*

INTRODUCTION AND RELATED WORK

The field of supply chain has experienced a rise in consumer awareness of environmental consciousness, which has led to legislation that holds the original equipment manufacturers (OEM) responsible for the end-of-life products. The number of products discarded by consumers has been steadily growing (Vadde *et al.*, 2006; Ilgin and Gupta, 2010).

Issues such as rising energy prices, finite resources, climate change, increasing emissions, disposal capacities, growing population, and improving quality of life have motivated both corporations and academics to develop strategies based on corporate social responsibilities and sustainable supply chains (Carter, 2008; Nagurney et al., 2007; Paul R. Kleindorfer et al., 2005). While the concept of integrating sustainability into supply chain is relatively new, it's implementation is nevertheless increasing continuously (Seuring et al., 2008).

Nowadays, while the products are still moving in the direction of the end customer the reverse flow of products is also taking place. This is clearly noticeable in most of the industrial sectors, especially in electronic products, automobiles, pharmaceuticals and beverages. The automobile industry, for example, has embraced the changes in the supply chain to smooth the end-of-life vehicles recovery and the US vehicle recycling infrastructure (Boon et al., 2000; Ferguson and 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 (Alkhayyal and Gupta, 2015; Gupta, 2013; Ilgin and Gupta, 2010).

According to Seuring and Muller (2008) a sustainable supply chain is '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, i.e., 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. Environmental sustainability is preventing environmental damages from happening and by enforcing Greenhouse Gas (GHG) emissions regulations. The social dimension includes, but not limited to, the reduction in negative consequences of the spread of disease, noise, traffic congestion, stress, coastal destruction and the improvement in the quality of life.

Mexiell and Gargeya (2005) conducted a literature review on economic considerations of supply chain design. Seuring and Muller (2008), Srivastava (2007) presented a comprehensive review of the published literature on sustainable supply chain.

Recent available literature reviews considering different aspects on supply chain sustainability include: energy use (Dotoli, 2005), GHG emissions reduction (Ferretti et al., 2007), (Guillen and Grossmann, 2009), green design (Hugo and Pistikopoulos, 2005), (Hugo et al., 2005), production planning and control for remanufacturing (Jayaraman et al., 1999, (Luo et al.,2001), product recovery (Jayaraman, 2006), reverse logistics (Sheu et al., 2005), (Sheu, 2008) inventory management (Ferretti et al., 2007), and waste management (Ferretti et al., 2007).

Environmentally conscious manufacturing and product recovery issues have been addressed in Gungor and Gupta (1999) with an extensive review of the literature. They include 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). They looked at the product recovery process from environmentally conscious manufacturing point of view. Ilgin and Gupta (2010) further extended this literature review through 2010.

Other authors who reported on product recovery designs under certain legislation and regulations include: (Fleischmann et al., 2001); (Das, 2002); (Bellmann and Khare, 2000); (Dekker and Fleischmann, 2004); (Fleischmann, 2000); (Guide et al., 1999 & 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 about cost, service, quality and carbon," Chaabane et al (2012). A Closed-loop supply chain (CLSC) network considered by Paksoy et al. (2011), focused on the transportation logistics cost and their GHG emissions. The study examined the trade-off between operational and environmental performance measures.

The carbon emissions because of the supply chain network design and supplier selection using life-cycle assessment (LCA) approach, has been investigated by Abdallah et al. (2012).

Diabat and Simichi-Levi (2010) formulated a mixed-integer program to find an optimal strategy for companies to meet their carbon cap, while minimizing cost. Chaabane et al. (2012) examined the carbon emissions impact on designing a sustainable CLSC network based on LCA principles. The model was based of aluminium firm to evaluate the tradeoffs between economic and environmental dimensions under various cost and strategies. Diabat et al. (2013) considered the issues of facility location problem in CLSC with a trading price of carbon emissions and a cost of procurement. 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 expressed in terms of dollar carbon cost.

Benjaafar et al. (2013) introduce a series of lot sizing models to illustrate how carbon emission impacts could be integrated into operations decisions and how significant emissions reductions without increases in costs can be achieved by operational adjustments alone.

Jin et al. (2014) studied the carbon policies impact on supply chain and transportation mode selection decisions for a major retailer.

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 and minimize the CO2 emissions, based on actual sites in the Boston area. The proposed model considers a mid-sized LG brand air conditioning (A/C) unit with a refurbished market price of $288. Valuation of emissions is done by using a direct carbon tax with the value varied according to ranges proposed in the 21st Climate Change Conference (COP21) in Paris by US Interagency Working Group (2013) and US Environmental Protection Agency (2015), to determine how proposed policy will influence profit margins for remanufactured goods.

NOMENCLATURE

The nomenclature used in this paper is given below:

Variables	**Definition**
$S1$	Space occupied by unit of remanufactured unit;
$S2$	Space occupied by unit of used-product;
CAP_v	Capacity of remanufacturing facility *v* to remanufacture products;
R_{ut}	Cost per unit retrieved at collection center *u*;
SH_u	Shortage cost at collection center *u*;
H_u	Holding cost at collection center *u*;
D_w	Demand of re-processed products in reselling center *w*;
X_{uv}	Decision variable representing the number of units to be transported from collection center *u* to remanufacturing facility *v;*
Z_{vw}	Decision variable representing the number of units to be transported from remanufacturing facility *v* to reselling center *w*;
P_v	Cost of re-processing per unit at remanufacturing facility *v;*
C_u	Storage capacity of collection center *u* for used units;
C_{1v}	Storage capacity of remanufacturing facility *v* for remanufacturing units;
C_{2v}	Storage capacity of remanufacturing facility *v* for used units;
C_w	Storage capacity of reselling center *w* for remanufactured units;
SUP_u	Supply at collection center *u*;
TX_{uv}	Cost of transporting per unit from collection center *u* to remanufacturing facility *v;*
TZ_{vw}	Cost of transporting per unit from remanufacturing facility *v* to reselling facility *w;*
CX_{uv}	CO_2 emissions per unit of shipping from collection center *u* to remanufacturing facility *v*, in tons per mile;
CX_{vw}	CO_2 emissions per unit of shipping from remanufacturing facility *v* to reselling center *w*, in tons per mile;
CY	CO_2 emissions factor of a remanufacturing facility *v*, in tons per ft3;
CZ	CO_2 emissions factor of a remanufacturing facility *v*, in tons per KWh of operation;

EX_u	Cost of energy per unit at collection center *u;*
EY_w	Cost of energy per unit at remanufacturing facility *v;*
EZ_w	Cost of energy per unit at reselling center *w;*
RX_u	Cost of rent per unit at collection center *u;*
RY_v	Cost of rent per unit at remanufacturing facility *v;*
RZ_w	Cost of rent per unit at reselling center *w;*
LX_u	Cost of labor per unit at collection center *u;*
LY_v	Cost of labor per unit at remanufacturing facility *v;*
LZ_w	Cost of labor per unit at reselling center *w;*
u	Collection center;
v	Remanufacturing facility;
w	Reselling center;
Y_v	Binary variable (0/1) for selection of remanufacturing facility *v*.

PROBLEM FORMULATION

The model is formulated as a single period 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 and minimize the CO_2 emissions, based on actual sites in the Boston area. The final demand for the product is met either with new or remanufactured products.

Minimize

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

Transportation cost $\sum u \sum v\, TX_u\, X_{uv} + \sum v \sum w\, TZ_u\, Z_{uv} +$

Remanufacturing cost $\sum v \sum w\, P_v\, z_{vw} +$

Inventory cost $\sum u + \sum v Ru * X_{uv} + \sum v + \sum w Pv * Z_{uv} + \{(D_W - SUP_u) * (Y)\} * H_u +$

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 $\sum u \sum EX_u + \sum v \sum EY_v + \sum w \sum EZ_W +$

CO_2 emissions $\sum u \sum v\, CX_u\, X_{uv} + \sum v \sum w\, CX_v\, X_{vw} + \sum CY + \sum CZ +$

Shortage cost $\{(D_W - SUP_u) * (1 - Y)\} * SH_u$ (1)

Subject to

Demand must be met.

$$\sum_v Z_{vw} \geq D_w \ ; \ \forall\, w \quad (2)$$

Total output is at most its total input.

$$\sum_u X_{uv} \geq \sum_w Z_{vw} \ ; \ \forall\, v \quad (3)$$

Total space is at most its capacity, at each remanufacturing facility.

$$\sum_w S_1 . Z_{vw} \leq C_{1v} . Y_v \ ; \ \forall\, v \quad (4)$$

$$\sum_u S_2 . X_{uv} \leq C_{2v} . Y_v \ ; \ \forall\, v, \quad (5)$$

Total space is at most its capacity, at each collection center.

$$\sum_v S_2 . X_{uv} \leq C_u \ ; \ \forall\, u \quad (6)$$

Total space is at most its capacity, at each reselling center.

$$\sum_v S_1 . Z_{uv} \leq C_w . Y_w \; ; \; \forall \, w \tag{7}$$

Non-negativity constraint.

$$X_{uv} \geq 0 \; ; \; \forall \, u, v \tag{8}$$

Total output is at most its capacity to remanufacture.

$$Z_{uv} \geq 0 \; ; \; \forall \, w, v \tag{9}$$

Total number of units supplied to remanufacturing facilities is at most by collection center.

$$\sum_w Z_{wv} \leq CAP_v \; ; \; \forall \, v \tag{10}$$

$$\sum_v X_{wv} \leq SUP_u \; ; \; \forall \, u \tag{11}$$

NUMERICAL EXAMPLE

The numerical example considers a single period situation of three collection centers, two remanufacturing facilities, and three reselling centers. For a mid-sized LG A/C unit model LW1213ER with dimensions of 23 5/8" x 15" x 22 1/6", a refurbished market price is $288. Valuation of emissions is done by using a direct carbon tax, with the value varied according to ranges proposed in the COP21 climate talks in Paris, by US Interagency Working Group (2013) and US Environmental Protection Agency (2015), to determine how proposed policy will influence the profit margins for remanufactured goods. The data used for implementing the model is shown in tables 1, 2 and 3.

Table 1 - Collection Centers

City	**Melrose**	**Canton**	**Natick**
Rentable Square Feet (RSF) per $	$7.17	$8.11	$9.14
Space rent per year for 20,000 Sqft.	$143,400	$166,200	$182,800
Number of laborers	10	10	10
Labor cost per year *	$187,200	$187,200	$187,200

**Labors: Massachusetts/Minimum wage 9.00 USD per hour (Jan 1, 2015)*

	City	**Taunton**	**Hingham**
Distance per mile	**Melrose**	52.76	28.10
Mile per gallon		8.79	4.68
Emissions of CO2 kg per gallon		78.31	41.69
Gasoline price per gallon		$18.83	$10.02
	City	**Taunton**	**Hingham**
Distance per mile	**Canton**	17.25	19.30
Mile per gallon		2.87	3.21
Emissions of CO2 kg per gallon		25.57	28.60
Gasoline price per gallon		$6.15	$6.87

	City	Taunton	Hingham
Distance per mile	**Natick**	36.90	30.55
Mile per gallon*		6.15	5.09
Emissions of CO2 kg per gallon**		54.79	45.35
Gasoline price per gallon***		$13.21	$10.93

** The average new heavy-duty truck got six miles per gallon*

*** Unleaded gasoline emits 8.91 kg of CO2 per gallon*

**** Massachusetts gas price average $2.143 per gallon (October 2015)*

Table 2 - Remanufacturing Facilities

City	Taunton	Hingham
Rentable Square Feet (RSF) per $	$6.74	$9.11
Space rent per year for 280,000 Sqft.	$1,887,200	$2,550,800
Number of laborers	500	500
Labors cost per year	$9,360,000	$9,360,000

	City	Revere	Boston	Somerville
Distance per mile	**Taunton**	44.86	39.70	43.00
Mile per gallon		7.48	6.62	7.17
Emissions of CO2 kg per gallon		66.62	58.95	63.86
Gasoline price per gallon		16.06	14.21	15.39
	City	**Revere**	**Boston**	**Somerville**
Distance per mile	**Hingham**	24.00	18.70	21.90
Mile per gallon		4.00	3.12	3.65
Emissions of CO2 kg per gallon		35.64	27.77	32.52
Gasoline price per gallon		8.57	6.68	7.82

Table 3 - Reselling Centers

City	Revere	Boston	Somerville
Rentable Square Feet (RSF) per $	$12.75	$36.75	$22.5
Space rent per year for 10,000 Sqft.	$127,500	$367,500	$225,000
Number of laborers	10	10	10
Labors cost per year	$187,200	$187,200	$187,200

RESULTS

In the absence of a carbon tax, the profit margin for the A/C unit is 26%, whereas a USEPA-recommended $40/ton CO2 equivalent ($CO_{2e}$) tax reduces the profit margin to 22%. LINGO 13.0 was used to solve the problem. The results obtained are shown in tables 4 and 5.

Table 4. Optimal Number of Units transported from Collection Center $_u$ to Remanufacturing Facility $_v$

City	Taunton	Hingham
Melrose	0	211
Canton	200	11
Natick	0	28

Table 5. Optimal Number of Units transported from Remanufacturing Facility $_v$ to Demand Center $_w$

City	Revere	Boston	Somerville
Taunton	50	0	150
Hingham	50	200	0

The optimal cost is $33339.46 ($74 per unit). The emission quantity relative to this solution is 0.07 ton CO2 equivalent (tCO_{2e}) per unit.

CONCLUSION

This paper presented an optimization model for reverse supply chain designed to understand the influence of both supply chain strategic and operational activities on the environment. A numerical example was considered to examine the performance of the model and to determine how the proposed policy would influence the profit margins for remanufactured goods. The results indicated that the carbon tax policy forces a strict constraint on the amount of carbon emissions generated in supply chain operations. Future research is in progress to breakdown 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.

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