Volume 2, Number 4, 2013

International Journal of Research in Industrial Engineering

journal homepage: www.nvlscience.com/index.php/ijrie

Closed-Loop Supply Chain Network with Green Supplier Selection and Disassembly of Products: A Bi-Objective Model

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A R T I C L E I N F O

Article history :
Received:
September 30, 2013
Revised:
December 19, 2013
Accepted:
January 15, 2014

Keywords :

reverse logistics, network design, green supplier selection, bi-objective.

A B S T R A C T

This paper aims to study the impact of product greenness and part reliability on reverse supply chain network through green supplier selection and disassembly of products. It proposes a bi-objective mathematical modeling for a closed-loop supply chain network considering green supplier selection and disassembly of products to trade-off profit and greenness. To our knowledge, this study is the first paper which considers the greenness of products in part/components level. So, some important issues such as part reliability, part greenness and inventory management of new and recovered parts are included into the model. Part reliability and part greenness are considered as green criteria in green supplier selection stage. Product greenness is defined according to design for disassembly level. Better design for disassembly means more greenness level for the products and better yield of parts at the disassembly stage. Green parts are made of highly recyclable materials. According to the part greenness and part reliability, some scenarios are defined. The greenness level of product is chosen by the model. ε-constraint method is applied to solve the model. A set of Pareto-optimal solution is obtained by using ε-constraint method to show the trade-off between the profit and greenness objectives. The results showed the efficiency of the model.

1. Introduction

The management of end-of-life products, also called reverse logistics [1], is very relevant in today's environmentally conscious manufacturing sector. According to the Reverse Logistics Executive Council [2], reverse logistics (RL) is "the process of planning, implementing, and controlling the efficient, cost effective flow of raw materials, in-process inventory, finished goods and related information from the point of consumption to the point of origin for the purpose of recapturing value or proper disposal".

Traditional supply chain network design (SCND) in forward flow includes determining the numbers, locations and capacities of production/manufacturing/distribution facilities, buffer inventories in each facility and the quantity of flow between them [3]. In backward networks and closed-loop networks (where the backward network is integrated with the forward

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network), other facilities such as collection depots, inspection and recovery centers are added to the facilities already set up for in the forward supply chain. Due to the fact that designing the forward and reverse flow separately results in sub-optimal designs with respect to objectives of supply chains, the design of forward and reverse logistics should be integrated ([4] and [5]).

An important issue in SCND is the establishment of appropriate performance measures to determine the efficiency and/or effectiveness of the current system in comparison with alternative systems. Traditionally, the focus of SCND problems has usually been on a single objective, namely minimizing cost or maximizing profit. Other measures sometimes considered in supply chain design are: the maximization of customer service level, minimization of financial risk and maximization of quality level. The integration of the RL loop yields new performance measures such the level of recyclability, remanufacturing flow. It is therefore very common to encounter models with two or more performance measures.

In supply chain management (SCM), many organizations have resorted to outsourcing suppliers in recent years as it appeared to be more profitable. There are significant differences between supplier selection in forward flow and supplier selection in backward flow and even more when compared to supplier selection in closed-loop network. Criteria relating to greenness and recyclability have higher importance in closed-loop network design. Thus, criteria such as reliability, recyclability, ease of disassembly should be taken into account for supplier selection in closed-loop supply chains.

Since companies also like to present a green image of their own manufacturing and distribution activities, including both profit and greenness objectives helps the decision maker make necessary trade-offs.

The reliability levels of the parts have a direct impact on the quality of the components found in returned products. Parts with higher reliability levels will survive their usage at the consumers' hands and will therefore be in better state when disassembled yielding a higher ratio of parts being available to be reused. Products made of parts with higher reliability will be easier and less expensive to refurbish and reuse.

Many models dealing with the design of logistics network are based on inventory planning and facility location theory. These models range from simple single-part, single-product, single-period incapacitated models (e.g., [6], [7]) to complex multi-part, multi-product, multi-period capacitated models. Ko and Evans [8] present a comprehensive literature review on logistics network design to support a variety of future research directions.

A large portion of the literature in logistics network design deals with reverse logistics network design and is aimed at determining the number of collection, recovery and disposal centers, and the optimized reverse flow from customers to recovery and disposal centers (e.g. see [9], [10], [11], [12]). Jayaraman et al. [11] develop a model to solve the single product two-level hierarchical location problem involving the reverse supply chain operations of hazardous products. Patia et al. [13] propose a mixed integer goal programming (MIGP) model to assist in the design of a multi-product paper recycling. The objectives considered are reduction in reverse logistics cost; product quality improvement through increased segregation at the source; and environmental benefits through increased wastepaper recovery.

The proposed model also assists in determining the facility location, route and flow of different varieties of recyclable wastepaper in the multi-item, multi-echelon and multi-facility decision making framework.

The concept of closed-loop supply chains is now widely garnering attention as a result of the recognition that both the forward and reverse supply chains need to be managed jointly. The configuration of both the forward and reverse supply chain networks has a strong influence on their performance. Since separating the forward and reverse design may result in sub-optimality, therefore, the two designs should be integrated [14]. Ko and Evans [8] present a MINLP model for the design of a 3PL (third party logistics) dynamic integrated forward/reverse logistics network. They propose a genetic algorithm-based heuristic to solve the complex model developed. Lee and Dong [15] develop a MILP model for integrated logistics network design for end-of-lease computer products. They consider a simple network with a single production center and a given number of hybrid distribution - collection facilities to be opened. They solve their model using Tabu search.

Finally, El-Sayed et al. [16] present a stochastic mixed-integer linear programming model for integrated forward/reverse logistics network design under demand and return uncertainty with the objective of maximizing total profit.

Minimization of cost or maximization of profit as objective function is the most commonly used objective function in the literature (e.g. [17], [18]). Multi-objective models have been developed by some authors for CLSCN. Cost and other objective functions such as responsiveness and supplier scores are considered. [19] develop a bi-objective mixed integer programming formulation to minimize the total costs and maximize the responsiveness of a logistics network. [20] propose a multi objective mixed-integer linear programming model to determine which suppliers and refurbishing sites should be selected (strategic decisions), and find out the optimal number of parts and products in CLSCN (tactical decisions). The objective functions aim to maximize profit, maximize weights of suppliers, and minimize defect rates.

A smaller number of papers address the issue of greenness. [13] formulate a mixed-integer goal programming model to determine the facility location, route and flow of different varieties of recyclable wastepaper CLSC network. They examine the minimization of the reverse logistics cost, maximization of the product quality improvement, and environmental benefits. [21] first developed a mixed-integer linear programming model that minimizes total cost. Then the model is extended to consider environmental factors including the use of environmental friendly materials by manufacturers and clean technology in collection centers.

Table 2 summarizes the literature review by presenting the key characteristics of the models reviewed above and the model proposed in our paper. The papers are classified according to the type of network, model features and objective functions. The acronyms used in Table 2 are first defined in Table 1. As shown in Table 2, a large proportion of papers consider single-objective functions, while a smaller proportion deals with multi-objective reverse SCND. Although, a few of the papers have considered environmental benefits as objective function, to the best of our knowledge, there is no study that addresses the greenness of parts and products in the objective function. Table 2 highlights the differences between our paper and the ones currently published.

Table 1. Acronyms used in Table 2

Category	Description	Acronym
Type of network	Reverse network	RN
	Closed-loop network	CLN
Features of the model	Multi-product or single-product	MPr or SPr
	Multi-part or single part	MPa or SPa
	Cost or Profit	C or P
Objective function of the model	Responsiveness	R
	Environmental benefits	E
	Part and product Greenness	G

Table 2 . Review of some existing models

Reference	Type of network		Features of model				Objectives of model			
	RN	CLN	MPr	SPr	MPa	SPa	C/P	R	E	G
[9]	✓			✓		✓	✓			
[11]	✓			✓		✓	✓			
[12]		✓	✓			✓	✓			
[13]	✓		✓			✓	✓		✓	
[8]		✓	✓			✓	✓			
[15]		✓		✓		✓	✓			
[17]		✓		✓		✓	✓			
[18]		✓		✓		✓	✓			
[19]		✓		✓		✓	✓	✓		
[21]		✓	✓			✓	✓		✓	
This paper (Our study, 2013)		✓	✓		✓		✓			✓

Based on the considerations described above, this paper presents a bi-objective model for closed-loop network. The objectives included are: profit and greenness. When a chain is green (has more opportunity to recover products), the result is that is it sometime more expensive because green sourcing is generally more expensive and recovery is also more expensive. However, a network with product recovery may also positively impact profit because the recovery network reduces the cost of after-sales service and creates a new market for refurbished products. Moreover, product recovery reduces environmental costs which are explicitly passed on by governments to companies.

Our model looks at three echelons in the forward direction (namely, suppliers, assembly centers and customer zones) and two echelons in the reverse direction (namely, disassembly and e-Recycling centers). It is a single period, multi-part, multi-product and multi-stage model. The rest of this paper is organized as follows: In Section 2, we define the problem to be modelled and solved. A bi-objective mixed-integer linear programming model of the logistic network design is developed and its set of Pareto optimal solutions obtained in Section 3. Section 4 presents a numerical example and discusses the computational results. Finally, we draw some conclusions from this work in Section 5.

2. Problem Statement

In this paper, a closed-loop supply chain network with suppliers, assembly centers, customer zones (CZ), disassembly centers and e-recycling centers is modelled and analyzed. It is assumed that suppliers, assembly centers, and disassembly centers are capacitated. The network is illustrated in Figure 1. Parts used in assembly centers are purchased from suppliers. Their prices are proportional to their reliability and greenness levels. Green parts are made of highly recyclable materials.

In each assembly center, a traditional assembly line already exists (no fixed cost required). There is the option of installing an additional assembly line which is used to assemble products that have been designed using Design for Disassembly (DFD) principles. A substantial fixed cost is incurred for this specialized assembly line to account for the additional costs incurred to design and assemble a product following the DFD principles, and the use of specialized connectors (quick release, fasteners, modularity, etc.) (see [22]). After assembly, products are shipped to customer zones. There are several flows of products which go to CZ based on the greenness level of products. The greenness level of the products is determined by the level of design for disassembly. Better design for disassembly means more greenness level for the products and better yield of parts at the disassembly stage with less time and therefore low disassembly cost. After using the products, customers return a proportion of them to collection centers/depots from where they are shipped to disassembly centers or e-recycling centers. The returned products shipped to the disassembly centers are disassembled yielding two types of parts: like-new parts that are re-injected into the forward loop at the assembly stage and scrapped parts that are shipped to e-recycling centers.

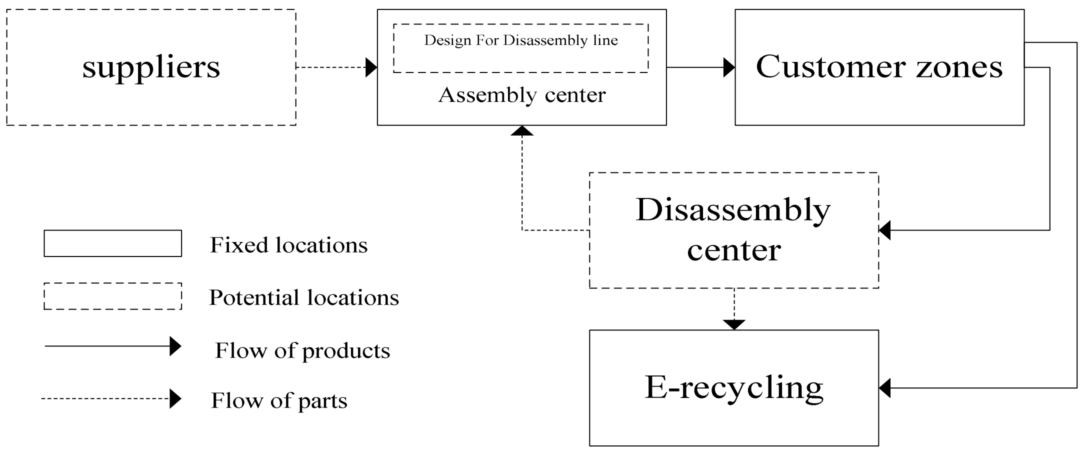

Figure 1: Closed-loop network under study

The following assumptions are made in the development of the model:

- Demand for products must be satisfied;
- The location of customer zones and e-recycling centers are fix and predefined;
- Refurbishing cost of like-new parts achieved by disassembly is included in disassembly cost;
- Disposal cost is included in shipping to e-recycling center cost;
- Products and parts have a greenness index denoted by the greenness level.

In this paper, we are interested in the role of reliability and greenness levels of products. When the reliability of parts is high, it may be more profitable to setup a reverse supply chain since the disassembly network will have a higher yield. When a product is green, it can be disassembled more easily, which also favours setting up a reverse supply chain. Furthermore, a green product may contain recyclable (green) parts, Therefore, negative shipping costs values are affected to recyclable parts shipped from disassembly centers to e-Recycling, which is equivalent to revenue being earned from the e-recyclers for sending green parts. When the greenness level of used parts is high, the model will disassemble more products instead of buying new parts from suppliers.

The reliability and greenness levels chosen for parts are considered as parameter. Scenarios will be defined according to the combinations of reliability and greenness levels. In this paper, 16 scenarios are defined from two levels of reliability, two levels of parts greenness, two types of parts and two levels of product greenness.

3. Model Formulation

The following notation is used in the formulation of the closed-loop supply chain network model.

Indices

S Index for potential suppliers s=1,…,S

P Index for part types p=1,…,P

M Index for product types m=1,…,M

A Index for existing locations of assembly centers with potential DFD line a=1,…,A

k Index for customer zones (CZ) k=1,…,K

l Index for potential disassembly centers l=1,…,L

g Index for greenness levels of material used to manufacture parts g=1,…,G

r Index for parts reliability levels r=1,…,R

d Index for products greenness levels d=1,…,D

Parameters

F_s Fixed suppliers selection cost

F_{mda} Fixed cost for setting up a DFD line for product m of greenness level d in assembly center a

F_l Fixed cost for opening disassembly center l

Π_{prgsa} FOB (Freight On Board) destination cost of part p with reliability level r and greenness level g shipped from supplier s to assembly center a

c_{mak} Unit shipping cost of product m from assembly center a to customer zone k
c_{mkl} Unit shipping cost of product m from customer zone k to disassembly center l
c_{pla} Unit shipping cost of like-new part p from disassembly center l to assembly center a
c_{pgl} Unit shipping cost of scrapped part p with greenness g from disassembly center l to e-recycling center
c^{e}_{mk} Unit shipping cost of returned product m from customer zone k to e-recycling center
B_{mda} Assembly cost for each product m with greenness level d at assembly center a
E_{mdl} Disassembly cost for each product m with greenness level d at disassembly center l
C_{prgs} Supplier s capacity for part p with reliability r and greenness level g
C_{mda} Assembly center a capacity for product m with greenness level d
C^{D}_{mdl} Disassembly center l capacity for product m with greenness level d
θ_{md} Fraction of good parts recovered from disassembly of product m with greenness level d
θ_{pr} Fraction of part p with reliability level r obtained by disassembly
σ_{prgm} Quantity of part p with reliability level r and greenness level g in one unit of product m
d_{mk} Demand in customer zone k for new product m
r_{md} Return rate of product m with greenness level d
ρ_{mk} Selling price of new product m in customer zone k
w Weight of profit objective function

Decision Variables

f_{prgsa} Quantity of parts p with reliability level r and greenness level g shipped from supplier s to assembly center a
f_{mda} Quantity of product m with greenness level d assembled at assembly center a
f_{mdak} Quantity of product m with greenness level d shipped from assembly center a to customer zone k
f_{mdkl} Quantity of product m with greenness level d returned from customer zone k and shipped to disassembly center l
f_{prgl} Quantity of scrapped part p with reliability and greenness levels r and g shipped from disassembly center l to e-recycling center
fprgla Quantity of like-new part p with reliability r and greenness g shipped from disassembly center l to assembly center a
o^{e}_{mdk} Quantity of product m with greenness level d returned from customer zone k and shipped to e-recycling center
f^{D}_{mdl} Quantity of product m with greenness level d disassembled at disassembly center l

$X_s \quad \begin{cases} 1 & \text{if supplier s is selected} \\ 0 & \text{otherwise} \end{cases}$

$Y_{mda} \quad \begin{cases} 1 & \text{if assembly line is open for product m with greenness level d at location a} \\ 0 & \text{otherwise} \end{cases}$

$Z_l \quad \begin{cases} 1 & \text{if disassembly center is open at location l} \\ 0 & \text{otherwise} \end{cases}$

The mathematical formulation of the network is described in the following lines. The two objective functions are presented and followed by the set of constraints.

$$\text{Maximize } Z_1 = \sum_{m\in M}\sum_{d\in D}\sum_{a\in A}\sum_{k\in K}\rho_{mk}\ f_{mdak} - \sum_{s\in S}F_s X_s - \sum_{m\in M}\sum_{d\in D}\sum_{a\in A}F_{mda} Y_{mda} - \sum_{l\in L}F_l Z_l$$
$$- \sum_{p\in P}\sum_{r\in R}\sum_{g\in G}\sum_{s\in S}\sum_{a\in A}\pi_{prgsa} f_{prgsa} - \sum_{m\in M}\sum_{d\in D}\sum_{a\in A}\sum_{k\in K}c_{mak} f_{mdak}$$
$$- \sum_{m\in M}\sum_{d\in D}\sum_{k\in K}\sum_{l\in L}c_{mkl} f_{mdkl} - \sum_{m\in M}\sum_{d\in D}\sum_{k\in K}c^e_{mk}\, o^e_{mk} - \sum_{p\in P}\sum_{r\in R}\sum_{g\in G}\sum_{l\in L}c_{pgl} f_{prgl}$$
$$- \sum_{p\in P}\sum_{r\in R}\sum_{g\in G}\sum_{l\in L}\sum_{a\in A}c_{pla} f_{prgla} - \sum_{m\in M}\sum_{d\in D}\sum_{l\in L}E_{mdl} f^D_{mdl}$$
$$- \sum_{m\in M}\sum_{d\in D}\sum_{a\in A}B_{mda} f_{mda} \text{ Type equation here.} \quad (1)$$

$$\text{Maximum } Z_2 = \sum_{m\in M}\sum_{k\in K}\sum_{d\in D}\sum_{a\in A} d\ \rho_{mk}\ f_{mdak} + \sum_{p\in P}\sum_{r\in R}\sum_{g\in G}\sum_{s\in S}\sum_{a\in A} g\ \pi_{prgsa}\ f_{prgsa} \quad (2)$$

Subject to:

$$\sum_{k\in K} f_{mdkl} = f^D_{mdl} \quad \forall m \in M, \forall d \in D, \forall l \in L \quad (3)$$

$$\sum_{s\in S} f_{prgsa} + \sum_{l\in L} f_{prgla} = \sum_{m\in M}\sum_{d\in D}\sigma_{prgm}\ f_{mda} \quad \forall p \in P, \forall r \in R, \forall g \in G, \forall a \in A \quad (4)$$

$$f_{mda} = \sum_{k\in K} f_{mdak} \quad \forall m \in M, \forall k \in K \quad (5)$$

$$\sum_{d\in D}\sum_{a\in A} f_{mdak} = d_{mk} \quad \forall m \in M, \forall k \in K \quad (6)$$

$$o^e_{mdk} + \sum_{l\in L} f_{mdkl} = r_{md}\sum_{a\in A} f_{mdak} \quad \forall m \in M, \forall d \in D, \forall k \in K \quad (7)$$

$$\sum_{m\in M}\sum_{d\in D}\sigma_{prgm}\ f^D_{mdl} = \sum_{a\in A} f_{prgla} + f_{prgl} \quad \forall p \in P, \forall r \in R, \forall g \in G, \forall l \in L \quad (8)$$

$$\sum_{a\in A} f_{prgla} = \theta_{pr}\sum_{m\in M}\sum_{d\in D}\theta_{md}\ \sigma_{prgm}\ f^D_{mdl} \quad \forall p \in P, \forall r \in R, \forall g \in G, \forall l \in L \quad (9)$$

$$f_{prgl} = \sum_{m\in M}\sum_{d\in D}(1-\theta_{md})\sigma_{prgm}\ f^D_{mdl} + (1-\theta_{pr})\sum_{m\in M}\sum_{d\in D}\theta_{md}\ \sigma_{prgm}\ f^D_{mdl} \quad (10)$$
$$\forall p \in P, \forall r \in R, \forall g \in G, \forall l \in L$$

$$\sum_{a\in A} f_{prgsa} \le C_{prgs} X_s \quad \forall p \in P, \forall r \in R, \forall g \in G, \forall s \in S \quad (11)$$

$$f_{mda} \le C_{mda} Y_{mda} \quad \forall m \in M, \forall d \in D, \forall a \in A \quad (12)$$

$$f^D_{mdl} \le C^D_{mdl} Z_l \quad \forall m \in M, \forall d \in D, \forall l \in L \quad (13)$$

$$f_{prgsa}, f_{mda}, f_{mdak}, f_{mdkl}, f_{prgl}, f_{prgla}, o^e_{mdk}, f^D_{mdl} \ge 0 \quad (14)$$

$$X_s, Y_{mda}, Z_l = \{0,1\} \quad (15)$$

The first objective (Eq. 1) is to maximize the total profit (total income minus total cost). The costs comprised the fixed cost for establishing the facilities, parts acquisition cost from suppliers, shipping costs, assembly and disassembly costs. The second objective (Eq. 2) seeks to maximize the total greenness including product and part greenness. The first term of Eq. 2 is the product greenness score and the second term is the part greenness score.

Constraint (3) is definition constraint showing that the total flow from all customer zones to a specific disassembly center is equal to the total amount of disassembled products in the disassembly center. Constraint (4) assures the flow balance of parts of given reliability and greenness levels in each assembly center. The left hand side of the equation show the total flow of parts purchased from suppliers and like-new parts which come from disassembly centers. The right hand side shows the total quantity of parts required for assembly. Constraint (5) shows that the total quantity of products assembled is distributed to all customer zones. Constraints (6) and (7) ensure that the demands of all customer zones are satisfied and products returned from all customer zones are collected and sent to disassembly or e-recycling centers. Constraints (8)-(10) assure the flow balance of parts at the disassembly centers. In constraint (8), the left hand side is the total quantity of parts required for disassembly, and right hand side is the total flow of like-new and scrapped parts going to assembly center and e-recycling, respectively. Constraints (9) and (10) show these two flows. Constraints (11)-(13) are capacity constraints on facilities. Finally, constraints (14) and (15) enforce the non-negativity and binary restrictions on corresponding decision variables.

4. Computational results

In this section, some numerical examples are presented to demonstrate the applicability of the mathematical model. We consider a network with 3 customer zones, 1 assembly center, 1 disassembly center, 2 suppliers, 2 types of parts with 2 reliability levels and 2 greenness levels each. The products being assembled can have two greenness levels: level 1 if assembled on the existing (traditional) line or level 2 if assembled on a DFD line. The purchasing costs of parts from different suppliers are known and directly proportional to their greenness and reliability levels. 16 scenarios depicted in Table 3 are generated using different combinations of reliability levels, greenness levels, and parts types. Two reliability levels and two greenness levels for each part and also two types of parts are considered.

The fixed cost of supplying both parts from suppliers is the same and equal to 50,000. The fixed cost of opening a DFD line in the assembly center is 100,000 and the fixed cost of opening the disassembly center is 300,000. The other parameters are reported in Table 4. All prices are in dollar.

Table 3. Scenarios based on the reliability and greenness levels of parts

Scenario number	Part 1		Part 2	
	Reliability level	Greenness level	Reliability level	Greenness level
1	1	1	1	1
2	1	1	1	2
3	1	1	2	1
4	1	1	2	2
5	1	2	1	1
6	1	2	1	2
7	1	2	2	1
8	1	2	2	2
9	2	1	1	1
10	2	1	1	2
11	2	1	2	1
12	2	1	2	2
13	2	2	1	1
14	2	2	1	2
15	2	2	2	1
16	2	2	2	2

Table 4. Parameters of the model

k	1	2	3	d	1	2
C_{mak}	2	3	3	C_{mda}	100000	200000
C_{mkl}	2	3	4	C^{D}_{mdl}	500000	100000
c^{e}_{mk}	200	200	200	B_{mda}	20	100
d_{mk}	30000	30000	30000	E_{mdl}	50	5
ρ_{mk}	300	300	300	r_{md}	0.4	0.4
				θ_{md}	0.4	0.8

p	r	g	s	Π_{prgsa}	C_{prgs}
1	1	1	1	50	500000
1	1	1	2	50	500000
1	1	2	1	75	500000
1	1	2	2	75	500000
1	2	1	1	75	500000
1	2	1	2	75	500000
1	2	2	1	100	500000
1	2	2	2	100	500000
2	1	1	1	60	500000
2	1	1	2	60	500000
2	1	2	1	85	500000
2	1	2	2	85	500000
2	2	1	1	85	500000

2	2	1	2	85	500000
2	2	2	1	110	500000
2	2	2	2	110	500000

p	r	g	σ_{prgm}
1	1	1	1
1	1	2	0
1	2	1	0
1	2	2	0
2	1	1	1
2	1	2	0
2	2	1	0
2	2	2	0

p	r	θ_{pr}
1	1	0.3
2	1	0.7
1	2	0.4
2	2	0.8

P	g	c_{pgl}
1	1	10
1	2	-5
2	1	10
2	2	-5

p	c_{pla}
1	3
2	2

The mathematical model is solved by GLPK (Gusek) on a Pentium dual-core 2.40 GHz computer with 4.00 GB RAM to generate different Pareto-optimal solutions using the ε-constraint method.

Pareto optimal trade-off between profitability and network greenness using the ε-constraint method

The payoff table displayed in Table 5 is generated by first calculating the individual optimum of each the objective function. Then, the profit is considered as the objective function and the greenness value is calculated, and vice versa.

Table 5. Payoff values for Scenario 1

	Profit (z_1)	Greenness (z_2)
Max profit (z_1)	12,719,920	36,338,400
Max greenness (z_2)	63,900,000	510,000

The range of the greenness objective function is divided into eight equal intervals and the nine grid points obtained are used as the values of ε in the ε-constraint method. Figure. 4 depicts the Pareto curve for profit versus greenness obtained for scenario 1. The profile is the same for the other scenarios. It can be seen in Figure. 4 that the profit value decreases with each increment in greenness value.

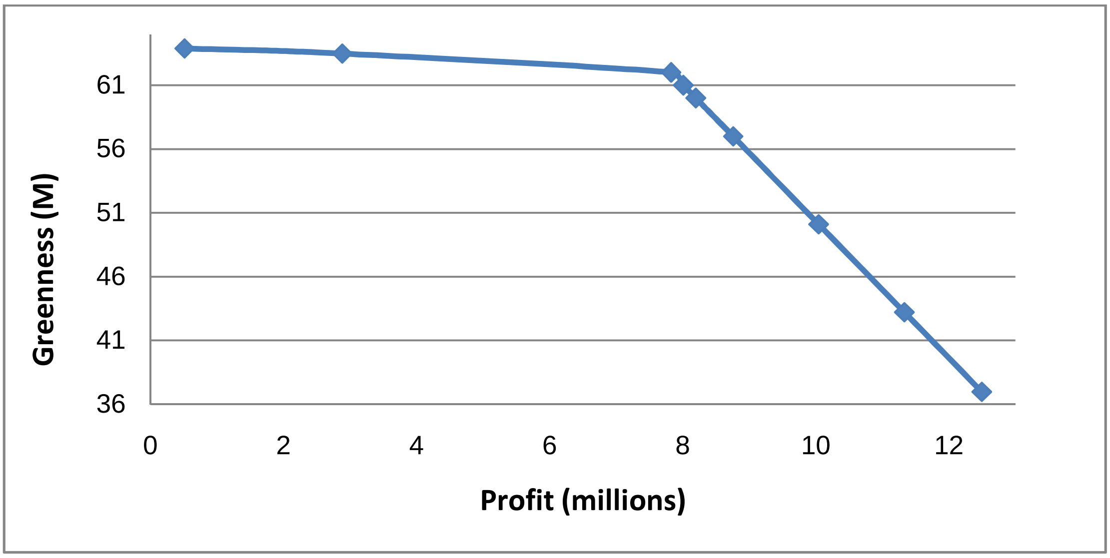

Figure. 4 Pareto-optimal solutions

Table 6. Payoff values for Scenario 16

	Profit (z_1)	Greenness (z_2)
Max profit (z_1)	6,275,920	60,249,600
Max greenness (z_2)	84,850,461	0

The greenness values in Table 6, Scenario 16, is higher than those in Table 5, Scenario 1, because in Scenario 16 the highest levels of reliability and greenness are chosen to assemble the product.

5. Conclusion

In this paper, a bi-objective mixed-integer linear programming model was developed and used to study the trade-offs between greenness and profit in a CLSCN. The model integrated the greenness of both parts and products and considered two levels for the ease of assembly/disassembly (Design for Disassembly DFD). Reliability and recyclability of the parts are accounted for in selecting the suppliers. The model determined which suppliers and disassembly centers should be selected, in which assembly centers parts are assembled to create products, which assembly centers required the opening of DFD assembly lines (strategic decisions) and the optimal number of parts and products in the network (tactical decisions). The set of Pareto-optimal solutions were generated by the ε-constraint method and showed the trade-offs between profit and greenness.
The literature of CLSCN design considering environmental-related objectives as well as profit is still in its infancy and this paper showed how greenness and profit considerations can be incorporated. Many possible future research directions can be defined. Many characteristics such as green packaging, clean technology, environmental certification of suppliers, may be considered in future models. Since in reality, some factors such as demand and returns are uncertain, stochastic, fuzzy and robust optimization can be incorporated in more realistic models. Extensions being investigated include a multi-period model with

inventory and material flow and a robust MILP for a multi-echelon multi-indenture multi-product CLSC model.

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