Decentralized Configuration, Pricing and Remanufacturing Decisions in a Multi-level Green Supply Chain

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Abstract - This paper incorporates remanufacturing decisions with pricing and supplier and component selection decisions in a multi-level green supply chain with multiple suppliers, one single manufacturer and multiple retailers. The manufacturer purchases optional components of a certain functionality from his alternative suppliers or remanufacture from recycled components and customizes a set of platform products for retailers in different independent market segments. The problem is modeled as a three-level Stackelberg game model. Analytical and genetic algorithm methods are introduced to determine the equilibrium. Finally, a case study is conduct to study the effectiveness of the proposed model and the effects of market potential parameter.

Keywords: Green supply chain, Stackelberg game, Configuration, Pricing, Remanufacturing.

1. Introduction

Green supply chain management refers to the effort to reduce the impact of business activities on environment (Swami and Shah 2013). Firms engaging in green supply chain management have experienced both environmentally and financially benefits. In China, many home appliance manufacturers, such as Galanz, Changhong, etc., reclaim wastes by way of trade-in to boost domestic demand in recent years. In addition to environmental regulation, remanufacturing requires only 20% of the energy, is estimated to save between 40 and 60% of the cost of manufacturing a completely new product (Inman 2002). The goal of this paper is to incorporate remanufacturing decisions with pricing and supplier and component selection decisions in a multi-level green supply chain with multiple suppliers, one single manufacturer and multiple retailers.

Green supply chain management has become a research paradigm in operations management (Srivastave 2007, Kuik *et al*. 2011, Ageron *et al*. 2012). Zhang *et al*. (1997) provide a comprehensive review of green design and show “Environmentally conscious design and manufacturing” brings safer and cleaner factories, worker production, improved product quality at lower cost, higher productivity, etc. Sarkis (2003) presents a strategic decision framework for green supply chain management. Srivastave (2007) comprehensively reviews a broad frame of literature of green supply chain. These studies on green supply chain management focus on the descriptive or behavioral aspects, while analytical modeling is not employed. Srivastava (2008) also proposes an integrated holistic conceptual framework which combines descriptive modeling with optimization techniques for network design in reverse logistics. Ageron *et al*. (2012) develop a theoretical framework to study sustainability in supply management and then study the framework by means of an empirical study using perceptions and practices of selected French companies.

Integrating supplier selection with product family design has gradually attracted attention from the scholars during the past several decades. Among them, Gupta and Krishnan (1999) develop an integer programming model to perform the integration of component and supplier selection for a product family. Huang *et al*. (2007) study optimizing the configuration of a set of platform products under the supply chain consisting of one manufacturer and multiple suppliers. Luo *et al*. (2011) further consider the joint optimization of component selection and supplier selection as a one-step approach. However, none of these research considers product family design and supplier selection in green supply chain setting.

Game theory is used to model green supply chain decisions in recent years. Savaskan *et al*. (2004) consider choosing appropriate reverse channel structure for the collection of used products from customers. They model the different collection options as decentralized decision-making systems with the manufacturer being the Stackelberg leader. Mitra and Wevster (2008) analyze a two-period model, where a manufacturer sells a new product and a remanufacturer competes with the manufacture in the second period. The authors study the impacts of government subsidy on remanufacturing activities. Ghosh and Shah (2011) examine the influence of channel structures on greening levels, prices and profits by game models and propose a two-part tariff contract to coordinate the green channel. Swami and Shah (2013) coordinate a manufacturer and a retailer in a vertical supply chain, where both players put in efforts for ‘greening’ their operations and the manufacturer acts as a Stackelberg leader. In the above research, price and level of green innovation/ reverse channel performance are the major factors studied in their reverse channel or green supply chain. Besides, these studies only consider the channel with single manufacturer and single retailer.

Our paper extends the above streams of research by specifically providing analytical model to coordinate price, remanufacturing, product family design and supplier selection in a three-level green supply chain environment. We consider conflict and coordination between green supply chain members undertaking remanufacturing initiatives as an important area of study. The manufacturer can purchase optional components of a certain functionality from his alternative suppliers or remanufacture from recycled components to produce a set of platform products that meet the requirements from the retailers in different market sectors. For the components, suppliers can procure a quantity of used components and then remanufacture them, or order new materials from external suppliers (as Fig. 1). The suppliers incur the cost of remanufacturing in our set-up. Each supplier faces the problem of deciding the component bidding prices and remanufacturing decisions for components that are geared towards the maximization of his net profit. The manufacturer selects the optimal suppliers and components as well as determines the wholesale prices and remanufacturing decisions to maximize his net profit. The retailers have to decide on the retail prices to maximize the profits.

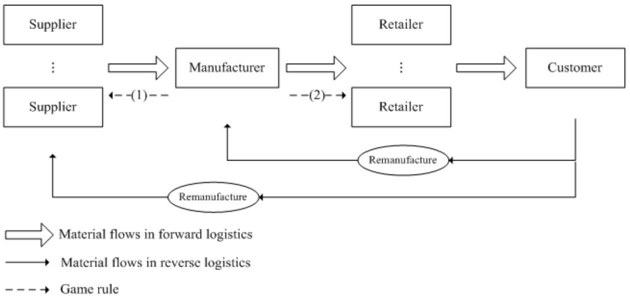

Fig.1. Basic activities in green supply chain

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The rest of the paper is organized as follows. In the next section, we detail our problem and present notations. In section 3, we introduce the game model. In section 4, we propose an analytical and GA method to solve the game model. We conduct numerical experiments to characterize the optimal solutions and effects of market potential parameter in Section 5. Section 6 concludes the paper and suggests topics for future research.

2. Problem description and notations

Consider a supply chain that consists of multiple suppliers, a single manufacturer and multiple retailers. The manufacturer, indicated by m, would like to design and customize a set of platform products for retailers (indicated by r , $r = 1, 2, ..., R$) in different independent market segments. Each retailer is served by one product customized from the product platform. The architecture for the product platform consists of a series of internal interfaces. For each interface, a number of product components with similar functionalities but different levels of performance or features are grouped together. The components within an interface can be ranked in order of decreasing functionality and higher functionality components can replace lower functionality ones completely, but not vice versa. We define the set of the components performed similar functionality in an interface as a replaceable component set (RCS). We assume that either all or none the demand of a component is replaced by the lower order component in the same RCS.

Assume that the manufacturer and the suppliers incorporate a remanufacturing process for used components into their original production system. Thus, the manufacturer can purchase optional components of a certain functionality from his alternative suppliers (v , $v = 1, 2, ..., V$) or remanufacture from recycled components to produce a set of platform products that meet the requirements from the retailers in different market sectors. For the components, suppliers can either directly produce a new component from raw materials or remanufacture part or whole from a returned unit into a new one.

Suppose that there are I RCSs and N_i components for the i^{th} RCS ($i = 1, 2, ..., I$). L_{ij} is used to denoted the component which is the j^{th} element in the i^{th} RCS, where $i = 1, 2, ..., I$ and $j = 1, 2, ..., N_i$. The v^{th} supplier offers a bidding price c_{vij} , of the j^{th} component in the i^{th} RCS. Particularly, c_{vij} is set as a large positive number if the v^{th} supplier does not supply the j^{th} component in the i^{th} RCS.

Let r_{vij} be the maximum amount of cost savings that the supplier v can attain using a used component to produce a new component L_{ij} . Similar to Savaskan and van Wassenhove (2004), component innovation requires upfront investment in remanufacturing, which is provided by the supplier. In defining ρ_{vij} as the fraction of this maximum cost reduction that results from an investment from the supplier v , ρ_{vij} is assumed to be a single value for the same component. The investment in innovation provided by each supplier for the component, which is quadratic in nature, is $\psi_{vij}\rho_{vij}{}^2$, where ψ_{vij} is the positive constant (Gilbert and Cvsa 2003). Thus, by investing $\psi_{vij}\rho_{vij}{}^2$, the supplier v can recover its component cost by $r_{vij}\rho_{vij}$ through recycling. This cost structure can be found in the literature (Gilbert and Cvsa 2003; Savaskan and van Wassenhove2004). Thus, the higher ρ_{vij} , the larger amount of investment in innovation and more cost recovered. For the manufacturer, the remanufacturing cost structures are similar.

The suppliers, manufacturer and retailers are assumed to be rational decision makers and the manufacturer, as a core enterprise of the supply chain, has dominant power over the other enterprises. The manufacturer decides on the wholesale prices, the suppliers selection decisions, the components selection decisions (i.e. whether to select higher functionality components to replace lower ones fixed a priori), and even the remanufacturing decisions to maximize his net profit. The suppliers determine the component prices and the fraction of the maximum cost reduction for each component. The retailers' problem will focus on the retail prices for the products. This can be addressed as a sequential game, which is actually composed of two sub-Stackelberg games. The first stackelberg game is played between the manufacturer and the suppliers, where the manufacturer, as a leader, can know the optimal decision processes / reactions of his suppliers and consider the reactions for maximizing his own profit. The second one is played between the manufacturer and the retailers. Similar to the first game, the manufacturer, as a leader, can know the best reactions of his retailers and consider the reactions for maximizing his own profit. The suppliers and retailers, as followers, react to the leader's decisions trying to make themselves profits maximized with their autonomies.

We also assume that single sourcing strategy (Tullous and Utrecht 1992) is adopted between supplies and manufacturer. Thus, the manufacturer purchases one type of component from only one supplier. Each supplier's capacity is assumed to be enough to satisfy the needs of the manufacturer.

To facilitate the modeling, the following other parameters and decision variables are used:

a_r : base market potential of retailer *r*

b_r : sensitivity of demand to price changes of retailer *r*

c_r : production cost per unit product *r*

q_r : retailer *r*'s demand

c_{vij} : price of component L_{ij} supplied by supplier *v*

u_{ijr} : predefined usage amount of unit component L_{ij} per unit product *r*

g_v : fixed cost of using supplier *v*, covering supplier certification, contract setup, etc.

p_r : decision variable, retailer *r*'s price

w_r : decision variable, manufacturer's wholesale price

Ω_v : number of different types of components supplier *v* is capable of supplying

τ_{ijk} : binary decision variable to indicate whether component L_{ij} is used to replace L_{ik}

ξ_v : binary decision variable to indicate whether supplier *v* is used

t_{vij} : binary decision variable to indicate whether component L_{ij} is supplied by supplier *v*

z_{ij} : binary decision variable to indicate whether component L_{ij} is used

π_r : retailer *r*'s profit

π_m : manufacturer's profit

π_v : supplier *v*'s profit

h_{ij} : manufacturer's maximum amount of cost saving from remanufacturing component L_{ij}

λ_{ij} : the fraction of this maximum cost reduction of the manufacturer for component L_{ij}

ϕ_{ij} : positive constant to illustrate the investment in innovation provided by manufacturer for the component, i.e. $\phi_{ij}\lambda_{ij}{}^2$.

3. Game model

3.1 Players' models

The retailer's objective is to maximize his net profit by optimizing his retail price. The following profit function is considered for the each retailer:

$$\text{Max } \pi_r = \left(p_r - w_r\right) q_r \qquad (1)$$

s.t.

$$q_r = a_r - b_r p_r \qquad (2)$$

$$p_r \geq 0 \qquad (3)$$

Constraint (2) is the demand function of each product. Constraints (3) set the value range of the pricing of each product.

The manufacturer takes on the cost of components, cost saving from innovation and investment for component innovation, production cost, and cost associated with adopting suppliers, such as negotiation, contract signing, and the investment in innovation for each component. The following profit function is considered for the manufacturer:

$$\begin{aligned}\text{Max } \pi_m = & \sum_{r=1}^{R} w_r q_r - \sum_{r=1}^{R}\sum_{v=1}^{V}\sum_{i=1}^{I}\sum_{j=1}^{N_i} p_{vij} z_{ij}\left(u_{ijl} + \sum_{k=j+1}^{N_i} u_{ikr}\tau_{ijk}\right) t_{vij} q_r \\ & + \sum_{r=1}^{R}\sum_{i=1}^{I}\sum_{j=1}^{N_i} h_{ij}\lambda_{ij} z_{ij}\left(u_{ijl} + \sum_{k=j+1}^{N_i} u_{ikr}\tau_{ijk}\right) q_r - \sum_{r=1}^{R} c_r q_r - \sum_{v=1}^{V} g_v \xi_v - \sum_{i=1}^{I}\sum_{j=1}^{N_i} \phi_{ij}\lambda_{ij}{}^2\end{aligned} \qquad (4)$$

s.t.

$$\sum_{j=1}^{k-1} \tau_{ijk} + z_{ik} = 1,\ \forall i = 1,2,...,I;\ j = 1,2,...,N_i - 1;\ k = j+1,...,N_i, \qquad (5)$$

$$\tau_{ijk} \leq z_{ij},\ \forall i = 1,2,...,I;\ j = 1,2,...,N_i - 1;\ k = j+1,...,N_i, \qquad (6)$$

$$\sum_{v=1}^{V} t_{vij} = z_{ij},\ \forall i = 1,2,...,I;\ j = 1,2,...,N_i - 1;\ k = j+1,...,N_i, \qquad (7)$$

$$\sum_{i=1}^{I}\sum_{j=1}^{N_i} t_{vij} \leq \Omega_v \xi_v,\ \forall v = 1,2,...,V, \qquad (8)$$

$$z_{ij}, t_{vij}, \xi_v = \{0,1\}, \forall i = 1,2,...,I;\ j = 1,2,...,N_i;\ v = 1,...,V, \qquad (9)$$

$$\tau_{ijk} = \{0,1\},\ \tau_{i,N_i,N_i+1} = \{0\}, \forall i = 1,2,...,I;\ j = 1,2,...,N_i - 1;\ k = j+1,...,N_i; \qquad (10)$$

$$w_r \geq 0, \forall r = 1,2,...,R. \qquad (11)$$

$$\lambda_{ij} \geq 0, \forall i = 1,2,...,I;\ j = 1,2,...,N_i. \qquad (12)$$

Constraint (6) ensures that a component is either used or replaced, but not both. Constraint (7) ensures that only procured components are used to replace other components. Both (6) and (7) guarantee that the demands for all components are satisfied. In addition, they meet the one-way substitutability constraint, which ensures that a higher-functionality component can replace a lower-functionality one, but not vice versa. Constraint (8) indicates that a component is procured from exactly one supplier. Constraint (9) sets the value of ξ_v as 1 on the condition that the supplier v supplies a component. Constraint (9) also ensures that the number of different types of components supplied by the supplier v is no greater than Ω_v. Value ranges of all variables are set by constraints (10), (11), and (12).

The supplier faces the cost of raw material purchasing, cost saving from innovation and investment for component innovation. $\sum_{r=1}^{R} z_{ij}\left(u_{ijr} + \sum_{k=j+1}^{N_i} u_{ikr}\tau_{ijk}\right) q_r t_{vij}$ is the total number of component L_{ij} used for all the products. The following profit function is considered for the supplier:

$$\text{Max } \pi_v = \sum_{r=1}^{R}\sum_{i=1}^{I}\sum_{j=1}^{N_i}\left(p_{vij} - c_{vij} + r_{vij}\rho_{vij}\right) z_{ij}\left(u_{ijr} + \sum_{k=j+1}^{N_i} u_{ikr}\tau_{ijk}\right) q_r t_{vij} - \sum_{i=1}^{I}\sum_{j=1}^{N_i} \psi_{vij}\rho_{vij}{}^2 \qquad (13)$$

s.t. $p_{vij} \geq 0$, $\rho_{vij} \geq 0$, $\forall i = 1,2,...,I;\ j = 1,2,...,N_i - 1.$
(14)

4. Solution algorithm

4.1 Best reactions of retailers and suppliers

To solve game model, we first use the analytical method to determine the best reactions of the retailers. Considering the second derivative of π_r with respect to p_r , we obtain $\frac{\partial^2 \pi_r}{\partial p_r{}^2} = -2b_l < 0$. The optimal p_r can be obtained by setting the first derivative of π_r with respect to p_r as equal to 0. Thus, we have:

$$p_r = \frac{a_r + b_r w_r}{2b_r}, \qquad (15)$$

and

$$q_r = \frac{a_r - b_r w_r}{2}. \qquad (16)$$

For each supplier, considering the second derivative of π_v with respect to ρ_{vij} , we obtain $\frac{\partial^2 \pi_v}{\partial \rho_{vij}{}^2} = -2\psi_{vij} < 0$. The optimal ρ_{vij} can be obtained by setting the first derivative of π_v with respect to ρ_{vij} as equal to 0. We have:

$$\rho_{vij} = \sum_{r=1}^{R} r_{vij} z_{ij}\left(u_{ijr} + \sum_{k=j+1}^{N_i} u_{ikr}\tau_{ijk}\right)\left(a_r - b_r w_r\right) t_{vij} / \psi_{vij} / 4 \qquad (17)$$

Substituting Eqs. (16) and (17) into Eq. (13), and calculating the second derivative of p_{vij} , we obtain $\frac{\partial^2 \pi_v}{\partial p_{vij}{}^2} = -2\sum_{l=1}^{L} b_l \left(z_{ij}\left(u_{ijl} + \sum_{k=j+1}^{N_i} u_{ikl}\tau_{ijk}\right) t_{vij}\right)^2 < 0$ for the supplier selected for component L_{ij} . Setting the first derivative of π_v with respect to p_{vij} , we obtain:

$$\begin{aligned}&\sum_{i=1}^{I}\sum_{j=1}^{N_i} p_{vij} z_{ij}\left(u_{ijr} + \sum_{k=j+1}^{N_i} u_{ikr}\tau_{ijk}\right) t_{vij} = \\ &\frac{a_r - b_r w_r}{b_r} + \sum_{i=1}^{I}\sum_{j=1}^{N_i}\left(c_{vij} - \frac{r_{vij}{}^2 z_{ij} t_{vij}}{4\psi_{vij}}\sum_{r=1}^{R}\left(u_{ijr} + \sum_{k=j+1}^{N_i} u_{ikr}\tau_{ijk}\right)\left(a_r - b_r w_r\right)\right) z_{ij}\left(u_{ijr} + \sum_{k=j+1}^{N_i} u_{ikr}\tau_{ijk}\right) t_{vij}\end{aligned} \qquad (18)$$

Substituting Eq. (18) into Eq. (4), π_m can be written as

$$\pi_m=\frac{1}{2}\sum_{r=1}^{R}w_r(a_r-b_rw_r)-\sum_{r=1}^{R}\frac{V(a_r-b_rw_r)^2}{2b_r}-\sum_{r=1}^{R}\sum_{v=1}^{V}\sum_{i=1}^{I}\sum_{j=1}^{N_i}\frac{1}{2}c_{vij}z_{ij}\left(u_{ijr}+\sum_{k=j+1}^{N_i}u_{ikr}\tau_{ijk}\right)t_{vij}(a_r-b_rw_r)$$
$$+\sum_{v=1}^{V}\sum_{i=1}^{I}\sum_{j=1}^{N_i}\frac{r_{vij}{}^2z_{ij}{}^2t_{vij}{}^2}{8\psi_{vij}}\left(\sum_{r=1}^{R}\left(u_{ijr}+\sum_{k=j+1}^{N_i}u_{ikr}\tau_{ijk}\right)(a_r-b_rw_r)\right)^2+\sum_{r=1}^{R}\sum_{i=1}^{I}\sum_{j=1}^{N_i}\frac{1}{2}h_{ij}\lambda_{ij}z_{ij}\left(u_{ijl}+\sum_{k=j+1}^{N_i}u_{ikr}\tau_{ijk}\right)(a_r-b_rw_r)$$
$$-\frac{1}{2}\sum_{r=1}^{R}c_r(a_r-b_rw_r)-\sum_{v=1}^{V}g_v\xi_v-\sum_{i=1}^{I}\sum_{j=1}^{N_i}\phi_{ij}\lambda_{ij}^2 \tag{19}$$

Considering the second derivative of Eq.(19) with respect to λ_{ij}, we obtain $\frac{\partial^2\pi_v}{\partial\lambda_{ij}{}^2}=-2\phi_{ij}<0$. The optimal λ_{ij} can be obtained by setting the first derivative of π_m with respect to λ_{ij} as equal to 0. We have:

$$\lambda_{ij}=\sum_{r=1}^{R}\frac{1}{4}h_{ij}z_{ij}\left(u_{ijr}+\sum_{k=j+1}^{N_i}u_{ikr}\tau_{ijk}\right)(a_r-b_rw_r)/\phi_{ij} \tag{20}$$

Substitute (20) into (19), we have:

$$\pi_m=\frac{1}{2}\sum_{r=1}^{R}w_r(a_r-b_rw_r)-\sum_{r=1}^{R}\frac{V(a_r-b_rw_r)^2}{2b_r}-\sum_{r=1}^{R}\sum_{v=1}^{V}\sum_{i=1}^{I}\sum_{j=1}^{N_i}\frac{1}{2}c_{vij}z_{ij}\left(u_{ijr}+\sum_{k=j+1}^{N_i}u_{ikr}\tau_{ijk}\right)t_{vij}(a_r-b_rw_r)$$
$$+\sum_{v=1}^{V}\sum_{i=1}^{I}\sum_{j=1}^{N_i}\frac{r_{vij}{}^2z_{ij}{}^2t_{vij}{}^2}{8\psi_{vij}}\left(\sum_{r=1}^{R}\left(u_{ijr}+\sum_{k=j+1}^{N_i}u_{ikr}\tau_{ijk}\right)(a_r-b_rw_r)\right)^2-\frac{1}{2}\sum_{r=1}^{R}c_r(a_r-b_rw_r)$$
$$-\sum_{v=1}^{V}g_v\xi_v+\sum_{i=1}^{I}\sum_{j=1}^{N_i}\frac{h_{ij}{}^2z_{ij}{}^2}{8\phi_{ij}}\left(\sum_{r=1}^{R}\left(u_{ijr}+\sum_{k=j+1}^{N_i}u_{ikr}\tau_{ijk}\right)(a_r-b_rw_r)\right)^2 \tag{21}$$

4.2 Genetic Algorithm

Genetic Algorithm (GA) is an efficient meta-heuristic algorithm with simple computation and robust search abilities for optimization problems (Mukhopadhyay *et al.* 2009). In this research, since the game model can be reformulated as Model A, we can develop a GA to solve the mixed-integer programming. The decision variables involved in the optimization model include continuous variables and 0–1 integer variables. The optimal values of the continuous variables are difficult to obtain by a genetic search alone (Defersha and Chen 2008). Thus, we first process the discrete variables in the heuristic search. Then, we use a nonlinear programming routine to determine the optimal value of the continuous variables by the given setting of discrete variables.

5. Numerical Study

5.1 Base example

In this section, we conduct a case study to illustrate how the model works in the proposed framework and gain some insights into the proposed model. This case is motivated by green manufacturing of a world-class electronics enterprise in Huizhou, China. In this section, we consider its television business, one of the three pillar businesses (i.e. television, mobile phone, and PC) of this enterprise.

A small set of data is prepared reflecting the real liquid crystal television (LC TV) business situation. The pricing data for the components are collected from the LC TV accessory stores in the biggest Chinese e-marketplace Alibaba (http://china.alibaba.com). Two types of products and six types of components from those products are included. The six types of components are 42-inch liquid crystal panel, mainboard, logic board, power panel, high-voltage switchboard and shell. The numbers of the alternate components in the RCSs are 4, 4, 3, 3, 3, and 3, respectively (as Table 1). The minimum component configuration requirements of both products are: Product 1 (3rd for RCS 1, 4th for RCS 2, 3rd for RCS 3, 3rd for RCS 4, 3rd for RCS 5 and 3rd for RCS 6); Product 2 (3rd for RCS 1, 3rd for RCS 2, 2nd for RCS 3, 3rd for RCS 4, 2nd for RCS 5 and 2nd for RCS 6).

The manufacturer considers the bidding prices and remanufacturing decisions of the qualified suppliers to make his configuration, remanufacturing and pricing decisions. The cost of adopting a supplier is $800 and the investment constant to remanufacture each component for the suppliers and the manufacturer are estimated to be $25,000 and $20,000 respectively. The crossover and mutation probabilities are set as 0.7 and 0.2 respectively. The other parameters are shown as Tables (A) in the Appendix.

The proposed GA is applied to solve the problem. The simplex algorithm is coded in Matlab. The results with a population of 120 and within 120 generations are shown in Fig. 4. At the beginning of the evolution, the average fitness value of the population improves from generation to generation. The algorithm reaches a highest point at approximately 40 generations, and fluctuates slowly thereafter. The optimal solution is obtained at the 58th generation. The optimal pricing, remanufacturing, and configuration results are given in Table 2.

Table 1. Components for the RCSs

RCS		Component			
		1st	2nd	3rd	4th
1.Liquid crystal panel (42-inch)	Brand	CHIMEI	LG	CHIMEI	LG
	Type	V420H2-LE3	LC420EUD-SDF1	V420H1-L11	LC420DUN
2.Mainboard	Brand	JX	JX	HX	CND
	Type	MST6M48	MTK8227-LB	TV2660	HD6361
3.Logic board	Brand	LG	AUMA	CH	
	Type	CK77-1394V-0	GS160.3	LJ41-08392A	
4.Power panel	Brand	CH	Delta	FSP	
	Type	HS368-4N01	DPS-165CP	135-4F01	
5.High voltage switchboard	Brand	CACHET	TYL	HIU	
	Type	INVERTER 8L	550TD240A01	812-M	
6. Shell	Brand	WH	WH	WH	
	Type	420F1	09J-4216W	XX420	

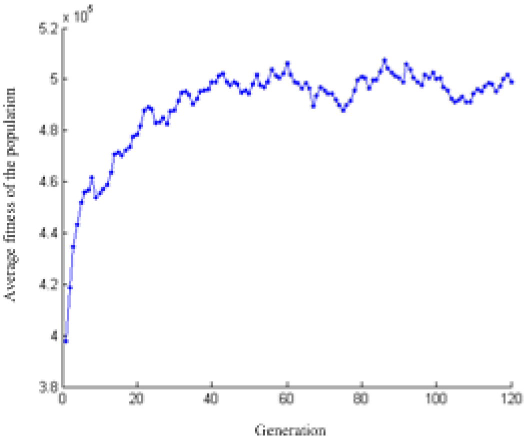

Fig. 4. Average fitness values of the generations

Table 2(a) lists the configuration results of the two product variants. For Product 1, the first component in RCS 6 is configured instead of the minimum configuration required components (i.e., third component in RCS 6). However, the manufacturer configures Product 2 in exactly the same as the minimum configuration requirement, and no higher-functionality components are used to replace the lower-functionality ones.

Table 2(a) also shows the optimal remanufacturing decisions. Supplier 12 and the manufacturer provide the largest fractions of the maximum cost reduction (i.e., 0.3402 and 0.6653) for the third component in RCS 1. This phenomenon is due to the large demand and high-value of this component, considering that it is used in both products. Besides, we can observe that the fraction of the maximum cost reduction for the manufacturer is almost twice as large as that of each selected supplier. Large fraction of the maximum cost reduction means large investment of the manufacturer / supplier in remanufacturing and more cost can be saved from remanufacturing.

Table 2(b) shows the pricing decisions, demands for both products and profits for the suppliers, the manufacturer and the retailers. We observe that due to the better market potential of Product 2, the demand of Product 2 is larger, although the prices for this product are much higher. For example, the retail price of product 2 is \$2,468.40, which is much higher than \$1,190.80 of product 1. However, its market demand is 632.00, higher than 230.00 of product 1.

Table 2. Configuration, remanufacturing, pricing decisions, demands and profits

(a) Configuration and remanufacturing decisions

RCS		1	2	3	4	5	6
Product 1	Component selected	3rd	4th	3rd	3rd	3rd	1st
	Supplier selected	12	11	1	9	6	8
	ρ_{vij}	0.3402	0.0129	0.0186	0.0211	0.0186	0.0523
	λ_{ij}	0.6653	0.0244	0.0419	0.0386	0.0349	0.1122
Product 2	Component selected	3rd	3rd	2nd	3rd	2nd	2nd
	Supplier selected	12	12	3	9	6	4
	ρ_{vij}		0.0131	0.0373		0.0243	0.0468
	λ_{ij}		0.0272	0.0630		0.0526	0.0876

(b) Pricing decisions, demands and profits

	w_i (\$)	p_i (\$)	q_i
Product 1	1,181.60	1,190.80	230.00
Product 2	2,436.80	2,468.40	632.00
Total suppliers' profit (\$)	1,060,800.00		
Manufacturer's profit (\$)	564,580.00		
Retailer 1's profit (\$)	2,116.00		
Retailer 2's profit (\$)	19,971.20		

5.2 Managerial implication

Based on the case study and its computational results and analyses presented above, some findings are observed. First, the manufacturer invests more in remanufacturing than the component suppliers. Second, the manufacturer would like to invest more in high-value component remanufacturing. Third, as the market potential of one product increases, the manufacturer tends to configure the product closer to the minimum requirements. Lastly, as market potential increases, the supplier and the manufacturer would like to invest more in remanufacturing, which will also increase the profits of all the retailers. This result signifies that the remanufacturing investment is closely related to market potential.

6. Conclusion

In this paper, we have presented a formulation for a coordination problem, which integrates supplier and component selection, pricing, and remanufacturing decisions in a green supply chain composed of multiple suppliers, one manufacturer and multiple retailers. The coordination problem is modeled as a Stackelberg game model. We use an analytical method and GA to derive the optimal decisions of all the chain members. A case study is conducted to study the effectiveness of the proposed mathematical model and its solving.

However, this paper has several limitations that can be extended in future studies. Although this paper covers product configuration, the competition among the different products is not considered. Under the competition, the demand of one product is not only the function of its own price, but also the prices of the other products. Second, we assume that the components can be ranked according to their functionalities, and either all or none of the demand of a component is replaced by the components with lower functionality in the same replaceable component set. Future research should relax the constraints by including the case in which the components can be partially replaced. In our set-up, although both the suppliers and manufacturer may benefit from remanufacturing, only the suppliers incur the cost of remanufacturing. We can extend the situation to that in which the manufacturer invests in remanufacturing as well.

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Appendix

Table A. Other parameters

(a) Market and production cost parameters

	Product 1	Product 2
a_r	30,000	50,000
b_r	25	20
c_r	5	6

(b) Components costs

Supplier	Components ($ cost)
1	c_{11} (422.08), c_{12} (340.91), c_{13} (308.44), c_{14} (284.09); c_{31} (48.70), c_{32} (35.88), c_{33} (16.23); c_{41} (56.82), c_{42} (29.22), c_{43} (19.48)
2	c_{21} (35.71), c_{22} (21.92), c_{23} (12.66), c_{24} (11.36); c_{61} (48.70), c_{62} (38.96), c_{63} (30.84)
3	c_{11} (446.42), c_{12} (324.68), c_{13} (292.21), c_{14} (243.51); c_{31} (40.58), c_{32} (32.47), c_{33} (9.74); c_{51} (35.71), c_{52} (19.67), c_{53} (16.23)
4	c_{21} (40.58), c_{22} (24.35), c_{23} (12.99), c_{24} (9.74); c_{41} (56.01), c_{42} (32.47), c_{43} (17.86); c_{61} (51.95), c_{62} (40.58), c_{63} (32.47)
5	c_{11} (438.31), c_{12} (373.38), c_{13} (316.56), c_{14} (300.32); c_{31} (45.45), c_{32} (37.34), c_{33} (17.86); c_{51} (35.71), c_{52} (24.35), c_{53} (16.23)
6	c_{21} (35.09), c_{22} (21.10), c_{23} (12.98), c_{24} (10.55); c_{51} (34.09), c_{52} (21.10), c_{53} (16.23)
7	c_{21} (33.86), c_{22} (22.18), c_{23} (10.90), c_{24} (9.64); c_{31} (43.34), c_{32} (35.14), c_{33} (15.85)
8	c_{11} (430.24), c_{12} (360.94), c_{13} (295.62), c_{14} (276.47); c_{31} (44.29), c_{32} (35.78), c_{33} (19.42); c_{51} (35.38), c_{52} (24.35), c_{53} (17.85); c_{61} (45.45), c_{62} (38.96), c_{63} (30.84)
9	c_{41} (58.23), c_{42} (35.65), c_{43} (18.24); c_{51} (38.96), c_{52} (26.75), c_{53} (17.98)
10	c_{11} (425.63), c_{12} (367.54), c_{13} (298.46), c_{14} (270.39); c_{31} (45.33), c_{32} (34.17), c_{33} (20.55); c_{61} (50.23), c_{62} (42.38), c_{63} (33.26)
11	c_{21} (30.84), c_{22} (23.24), c_{23} (14.51), c_{24} (11.29); c_{41} (55.41), c_{42} (37.25), c_{43} (20.11); c_{51} (40.03), c_{52} (20.36), c_{53} (14.67)
12	c_{11} (421.56), c_{12} (364.78), c_{13} (288.12), c_{14} (245.33); c_{21} (34.16), c_{22} (19.24), c_{23} (11.37), c_{24} (7.85); c_{31} (42.26), c_{32} (33.15), c_{33} (17.82); c_{41} (57.33), c_{42} (34.56), c_{43} (16.64); c_{51} (35.76), c_{52} (24.11), c_{53} (15.98)
13	c_{21} (35.12), c_{22} (24.87), c_{23} (12.33), c_{24} (11.55); c_{51} (39.44), c_{52} (25.61), c_{53} (16.97); c_{61} (52.27), c_{62} (41.35), c_{63} (32.39)

(c) Suppliers' maximum cost savings

Supplier	Maximum cost saving ($ cost)
1	r_{11} (28.14), r_{12} (22.73), r_{13} (20.56), r_{14} (18.94); r_{31} (3.25), r_{32} (2.39), r_{33} (1.08); r_{41} (3.79), r_{42} (1.95), r_{43} (1.30)
2	r_{21} (2.38), r_{22} (1.46), r_{23} (0.84), r_{24} (0.75); r_{61} (3.24), r_{62} (2.60), r_{63} (2.06)
3	r_{11} (29.76), r_{12} (21.65), r_{13} (19.48), r_{14} (16.23); r_{31} (2.70), r_{32} (2.16), r_{33} (0.65); r_{51} (2.38), r_{52} (1.31), r_{53} (1.08)
4	r_{21} (2.71), r_{22} (1.62), r_{23} (0.86), r_{24} (0.64); r_{41} (3.73), r_{42} (2.16), r_{43} (1.19); r_{61} (3.46), r_{62} (2.71), r_{63} (2.16)
5	r_{11} (29.22), r_{12} (24.89), r_{13} (21.10), r_{14} (20.02); r_{31} (3.03), r_{32} (2.49), r_{33} (1.19); r_{51} (2.38), r_{52} (1.62), r_{53} (1.08)
6	r_{21} (2.34), r_{22} (1.41), r_{23} (0.87), r_{24} (0.70); r_{51} (2.27), r_{52} (1.41), r_{53} (1.08)
7	r_{21} (2.26), r_{22} (1.48), r_{23} (0.73), r_{24} (0.64); r_{31} (2.89), r_{32} (2.34), r_{33} (1.06)
8	r_{11} (28.68), r_{12} (24.06), r_{13} (19.71), r_{14} (18.43); r_{31} (2.95), r_{32} (2.38), r_{33} (1.29); r_{51} (2.36), r_{52} (1.62), r_{53} (1.19); r_{61} (3.03), r_{62} (2.59), r_{63} (2.06)
9	r_{41} (3.88), r_{42} (2.38), r_{43} (1.22); r_{51} (2.60), r_{52} (1.78), r_{53} (1.20)
10	r_{11} (28.38), r_{12} (24.50), r_{13} (19.90), r_{14} (18.03); r_{31} (3.02), r_{32} (2.28), r_{33} (1.37); r_{61} (3.35), r_{62} (2.83), r_{63} (2.22)
11	r_{21} (2.06), r_{22} (1.55), r_{23} (0.97), r_{24} (0.75); r_{41} (3.69), r_{42} (2.48), r_{43} (1.34); r_{51} (2.67), r_{52} (1.36), r_{53} (0.98)
12	r_{11} (28.10), r_{12} (24.32), r_{13} (19.21), r_{14} (16.36); r_{21} (2.28), r_{22} (1.28), r_{23} (0.76), r_{24} (0.52); r_{31} (2.82), r_{32} (2.21), r_{33} (1.19); r_{41} (3.82), r_{42} (2.30), r_{43} (1.11); r_{51} (2.38), r_{52} (1.61), r_{53} (1.07)
13	r_{21} (2.34), r_{22} (1.66), r_{23} (0.82), r_{24} (0.77); r_{51} (2.63), r_{52} (1.71), r_{53} (1.13); r_{61} (3.48), r_{62} (2.76), r_{63} (2.16)

(d) Manufacturer's maximum cost savings

	Manufacturer's maximum cost saving ($ cost)
RCS 1	h_{11} (40.08), h_{12} (34.09), h_{13} (30.84), h_{14} (28.09)
RCS 2	h_{21} (3.57), h_{22} (2.19), h_{23} (1.26), h_{24} (1.13)
RCS 3	h_{31} (5.68), h_{32} (2.92), h_{33} (1.94)
RCS 4	h_{41} (5.60), h_{42} (3.25), h_{43} (1.79)
RCS 5	h_{51} (3.57), h_{52} (2.44), h_{53} (1.62)
RCS 6	h_{61} (5.20), h_{62} (4.06), h_{63} (3.23)

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