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Coordination of the closed-loop supply chain for product line design with consideration of remanufactured products

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Abstract

Research on integrated products and the closed-loop supply chain design has focused on the competition and coordination of manufacturers and supply chain partners. However, the coordination of supply chain partners for product line design (PLD) with consideration of remanufactured products has not been addressed in previous studies. The present study investigates the coordination of a manufacturer and supply chain partners using a game theoretical model for the design of product lines that contain both new and remanufactured products. A multiobjective optimization model based on Stackelberg game theory is formulated to determine the product line solutions, pricing decisions of supply chain partners, and product return rate for remanufacturing. A non-dominated sorting genetic algorithm II is introduced to determine the Pareto optimal solutions of the multiobjective optimization problems. A case study is conducted on the coordination of a manufacturer, chain retailers, and a remanufacturer for the PLD of tablet PCs with consideration of remanufactured tablet PCs to illustrate the applicability and effectiveness of the proposed methodology.

Keywords: product line design; closed-loop supply chain (CLSC); remanufacturing; Stackelberg game theory; multiobjective optimization; NSGA-II.

1. Introduction

Product line design (PLD) has been widely adopted by several companies in developing various product variants for different customer segments to satisfy increasing diversification of customer needs. PLD helps increase the profitability and market shares of products, which involves determining the number of product variants and their design attribute settings (Krishnan and Ulrich, 2001; Thevenot et al., 2007; Kwong et al., 2011). Marketing and engineering issues are commonly considered simultaneously in PLD problems (Luo, 2011). Some studies have been conducted on the closed-loop supply chain (CLSC) in product design.

A CLSC involves a collection of used products from customers and supports various product recovery strategies, such as remanufacturing, recycling and reuse, and managing the relationship and coordinating with supply chain partners, such as manufacturers, suppliers, retailers, and/or remanufacturers. Various studies on CLSC have focused on the evolution of CLSC (Guide and Wassenhove, 2009), CLSC relationships for product remanufacturing

(Ostlin et al., 2008), CLSC network design and coordination of supply chain parties (Souza, 2013), and integrated sustainable product and supply chain design (Metta and Badurdeen, 2013). As one of the most common product recovery strategy, remanufacturing refers to restoring returned products functionally and aesthetically to their original condition and in some cases even with better features. Only a limited number of studies have considered remanufactured products in the product design stage. Debo et al. (2006) established a modified Bass diffusion model to analyze the diffusion of new and remanufactured products in a given market. However, product design attributes were not considered in their study. Vorasayan and Ryan (2006) developed a queuing network-based optimization model to determine the product return rate and price of remanufactured products and to maximize profit. Ferrer and Swaminathan (2010) examined and compared the optimal policies for remanufacturing and pricing new and differentiated remanufactured products in a monopoly market for a two-period, multi-period, and infinite planning horizons; however, product design issue was not considered in their demand model . Shi et al. (2011) established a CLSC model with a single manufacturer to determine the amount of new and remanufactured products, their selling prices, and the procurement price of used products at which remanufactured and new products are sold in the same market at the same price. Kwak and Kim (2013) established a market positioning model for remanufactured products to determine the optimal settings and price of a remanufactured product. Since remanufactured products could cannibalize the sales of new products because of price advantages (Debo et al., 2006), consideration of remanufactured and new products should not be separate. Kwak and Kim (2015) extended their previous work by developing a decision-support model for determining optimal design of new and remanufactured products simultaneously and number of returned products in which the trade-off between total profit and environmental-impact saving was examined. Chen and Chang (2013) investigated the dynamic pricing strategy for new and remanufactured products in a CLSC considering the price-dependent market demand. Yalabik et al. (2014) examined the profitability of traditional and green companies in terms of market, cost, and product type conditions, where the green company produces remanufactured products for lease and secondary markets. Hatcher et al. (2011) reviewed the literature and defined future research needs in design for remanufacture in which end-of-life and lifecycle considerations were stated as essential issues in product design. Few studies have investigated the competition and cannibalization between new and remanufactured products (Vorasayan and Ryan, 2006; Atasu et al., 2008; Ostlin et al., 2009; Guide and Li, 2010). All the studies described above mainly focused on optimal product design and/or pricing of remanufactured products in a centralized case and they did not consider other supply chain partners apart from manufacturers.

Some studies have investigated the competition and coordination of original equipment manufacturer (OEM) and supply chain partners. Savaskan et al. (2004) examined three CLSC models with the Stackelberg leader, manufacturer, with respect to product collection performed by a manufacturer, retailer, and third party. Huang et al. (2007) established a game theoretical model to determine the configurations of a product line and supply chain that involves a single manufacturer and multiple suppliers. Esmaeili et al. (2009) analyzed the competition and cooperation between an OEM and a retailer through cooperative and non-cooperative Stackelberg game models. Huang and Huang (2010) conducted pricing analysis on a single product in a three-level supply chain model using the game theoretical approach with different power structures. Sadeghi and Zandieh (2011) formulated a game model to determine optimal product portfolio solutions considering the competition between two manufacturers. Bernard (2011) proposed a Nash equilibrium-based coordination model which involves two identical manufacturers and one remanufacturer in a duopoly market. Wu (2012a) investigated the price and service competition of a manufacturer, remanufacturer, and common retailer. Wu (2012b; 2013) later established game models to examine the competition between an OEM and a remanufacturer for product design and pricing decisions of new and remanufactured products. Swami and Shah (2013) studied channel coordination between a single manufacturer and retailer in a sustainable supply chain. Huang (2013) established a Stackelberg game model with multiple suppliers, single manufacturer and multiple retailers for an integrated product portfolio and CLSC design. Qiang et al. (2013) investigated the competition, coordination, and uncertainties of a CLSC with two suppliers, two manufacturers, and two retailers, in which both new and remanufactured products are launched in the same period. Ji et al. (2013) proposed a Stackelberg-based joint optimization model for green modular design with material reuse. Shi et al. (2011) investigated optimal design and production planning of a CLSC that involved multi-products under uncertain demand and return. Zeballos et al. (2014) conducted a similar study but considering a multi-period scenario under uncertain supply and demand . CLSC models have been examined with consideration of environmental and operational performance by De Giovanni and Zaccour (2014) and Chuang et al. (2014) in which the product collection is undertaken by manufacturers, retailers, or third-party firms Game theoretical models have been employed not only for the competition and coordination of supply chain members but also for product design. Choi and Desarbo (1993) employed Nash equilibrium in conjoint analysis to model competitive reactions in an optimal product design. Luo et al. (2007) developed a conjoint-based game model for new product positioning and pricing in the light of the channel acceptance of the retailer. Steiner (2010) proposed a Stackelberg-Nash game model based on conjoint data to examine the retaliatory reactions of competitors for new product design.

Although quite a number of previous studies considered the coordination of manufacturers and various supply chain parties in product development and CLSC, they did not address the two issues that need to be considered in product line design with consideration of remanufactured products; (1) the coordination among supply chain partners in performing PLD with consideration of remanufactured products in competitive markets, and (2) the joint effect of new and remanufactured product design and pricing on the estimation of market demands. In this paper, we propose a methodology for the coordination of a manufacturer, chain retailers, and a remanufacturer to undertake PLD that involves the determination of remanufactured products for maximizing the profit and market share of the product line. The proposed methodology can provide optimal solutions which contain specifications of new and remanufactured products, pricing decisions of supply chain parties and product return rate for remanufacturing.

The rest of the paper is organized as follows: Section 2 describes the proposed methodology for the coordination of a manufacturer, and supply chain partners for PLD with consideration of remanufactured products. Section 3 presents a case study on the coordination of a manufacturer, and supply chain partners for the PLD of tablet PCs, which involves remanufactured tablet PCs based on the proposed methodology. Section 4 shows the implementation results. A discussion of implementation results is provided in Section 5. Section 6 ends with the conclusion and directions for future work.

2. Proposed Methodology

Fig. 1 shows the CLSC considered in this study. The straight-line and dashed-line arrows indicate the forward and reverse flow of the supply chain, respectively.

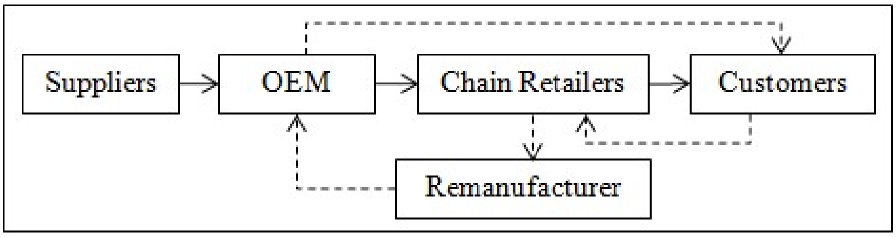

Fig. 1. Closed-loop supply chain.

The present research considers two types of markets are considered: the first and second market. The first market refers to a developed region where consumers are generally more interested in and willing to pay for brand new products than remanufactured products. The second market is normally a relatively less developed region where consumers generally may be unable to afford brand new products and may be interested in lower-priced remanufactured products. New products are launched only in the first market, whereas remanufactured products are launched only in the second market.

New and remanufactured products are launched at different times, or in two periods. New and remanufactured products are launched in markets in the first and second periods, respectively. In the first period, new products are produced by the OEM and sold to customers by chain retailers. Used or defected products are collected by chain retailers, who have a closer relationship with customers than the remanufacturer and OEM do. Chain retailers do not gain direct profits from remanufactured products, but they may gain profits through trade-in programs. The returned products are shipped to the remanufacturer, who pays the collect-back and transportation cost. In the second period, the remanufacturer refurbishes the collected products by changing some of their components and reconditioning them. The remanufactured products are then shipped to the OEM and sold in the second market.

A two-period Stackelberg game theoretical model is formulated to determine the setting of the decision variables including the number of new and remanufactured products to be offered, product attribute settings of the new and remanufactured products, wholesale and retail prices of the new products, wholesale and selling prices of the remanufactured products, and product return rate. Figs. 2(a) and 2(b) show the proposed methodology for the first and second periods, respectively. The methodology mainly involves conjoint analysis, generation of choice models, formulation of Stackelberg game and multiobjective optimization models, and solving optimization problems using non-dominated sorting genetic algorithm II (NSGA-II).

In the proposed methodology, conjoint analysis which is a popular technique for capturing consumer preferences and measuring tradeoffs is conducted to obtain customer preferences on products in the first and second markets. Survey respondents are classified into a number of individual market segments by using a K-means clustering technique which has been widely used in clustering and is easy to implement. The utility functions of the individual segments are thereafter generated through statistical regression. The multinomial logit (MNL) model is a highly popular choice model adopted in previous studies of decision based design (Wassenaar and Chen, 2003) is used to generate choice models together with the generated utility functions. The market potential is estimated based on the jury of the executive opinion method. Once the choice models are developed and the market potential estimates are obtained, demand models can be developed for both the first and second markets.

The OEM and chain retailers compete for the prices of new products in the first period, as shown in the proposed methodology for the first period shown Fig. 2(a). Since it is common that OEM is a focal company in a supply chain, the Stackelberg game theoretical model is adopted and incorporated into the proposed methodology. As the leader, the OEM determines the specifications and wholesale prices of the new products with consideration of the reaction function of the chain retailers. The retail prices of the new products are determined concurrently based on the reaction function of the chain retailers and determined specifications and on the wholesale prices of the new products. Two multiobjective optimization models respectively for the first and second periods need to be formulated.

NSGA-II is adopted to solve the optimization models. NSGA-II is highly capable of reducing computational complexity and providing a fast and effective constraint-handling strategy, which makes it one of the most efficient algorithm to solve multiobjective optimization problems (Murugan et al., 2009). The computational complexity is reduced by adopting fast nondominated sorting for fitness assignment. The quality of solutions and performance of the GA have been improved using elitism preservation strategy. Diversity ensuring mechanism has been enhanced by eliminating the parameter need (Deb et al., 2002). After the solving, Pareto optimal PLD solutions for the new products, market shares and profits of the PLD can be obtained.

Figure 2(b) outlines the proposed methodology for the second period. In this period, the OEM and remanufacturer compete for the prices of the remanufactured products. The OEM determines the specifications and selling prices of the remanufactured products with consideration of the reaction function of the remanufacturer and information of the new products. The wholesale prices of the remanufactured products are determined concurrently according to the remanufacturer's reaction function and determined specifications and to the selling prices of the remanufactured products. The market shares and profits of the product line solution for the remanufactured products can be obtained. The remanufacturer determines the product return rate according to the demand of remanufactured products in the second market and remanufacturability rate of the returned new products.

Details of the proposed methodology are described in the following sub-sections.

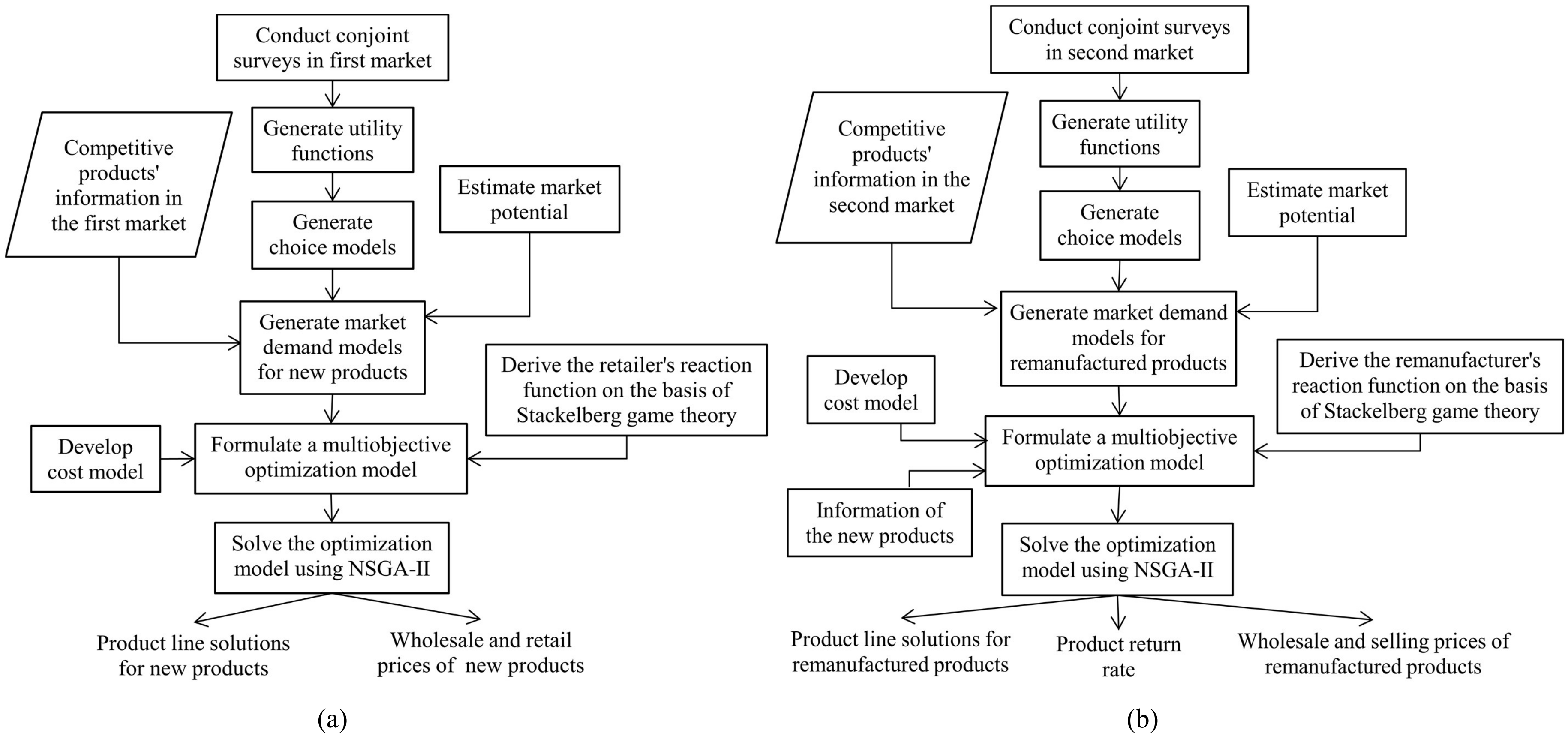

Fig. 2. The proposed methodology for the (a) first and (b) second periods.

2.1. Conjoint analysis

Conjoint analysis is conducted to capture consumer preferences on products by estimating the part-worth utilities for each level of product attributes (Chen et al., 2013). The utility functions of the products are generated through statistical regression based on the conjoint survey data:

$$U_{ij} = \sum_{k=1}^{M}\sum_{l=1}^{N_k} u_{ikl}x_{jkl} + f_{ij}^{pr}$$

where U_{ij} is the utility of the *j*-th product profile in the *i*-th segment; u_{ikl} is the part-worth utility of the *l*-th level of the *k*-th attribute in the *i*-th segment; f_{ij}^{pr} is the utility of the retail price of the *j*-th product in the *i*-th segment; *M* and N_k represent the number of attributes and number of attribute levels in the *k*-th attribute, respectively; and x_{jkl} denotes a dummy variable equal to 1 if the *l*-th level of the *k*-th attribute is selected for the product profile *j* and 0 otherwise.

In this study, the selling prices of products are defined as continuous variables. A curve-fitting method is introduced to generate the utility functions of the variables. The following shows an example of the utility functions of prices:

$$f_{ij}^{pr} = a_{i0} + a_{i1}p_j + a_{i2}(p_j)^2$$

where a_{i0}, a_{i1}, and a_{i2} are the coefficients of the quadratic polynomial function in the *i*-th segment; and p_j represents the price of the *j*-th product.

2.2. Development of market share models

MNL based choice model is is built on individual utility functions. The choice probabilities are constructed independently from irrelevant alternatives that fundamentally bring proportional substitution among alternatives and ignore the correlation among alternatives. Thus, the introduction or exclusion of an alternative will result in an equal percentage decrease or increase in the choice probabilities of all other alternatives in the choice set. This property provides a computational advantage in terms of adding or extracting alternatives in a choice set (Train, 2009). In this research, market share models are developed based on the following MNL model and generated utility functions:

$$MS_{ip} = \frac{e^{U_{ip}}}{\sum_{j=1}^{J} e^{U_{ij}} + \sum_{k=1}^{K} e^{U_{ik}} + e^{U_{ip}}}$$

where MS_{ip} is the probability of choosing the p-th product among the existing and competitive products of the company in the i-th segment; U_{ip} is the utility of the p-th product in segment i; U_{ik} is the utility of the k-th existing product in segment i; and U_{ij} is the utility of the j-th competitive product in segment i.

2.3. Development of cost models

The cost model for new product variants is developed based on SIMOPT models (Green and Kriger, 1992; Kwong et al., 2011), which estimate the part-worth cost for each level of product attributes. Two cost components are involved: fixed cost (c_p^f) and variable cost (c_p^v). The fixed cost is not affected by or not sensitive to the profiles of product variants, such as labor and overhead cost. The variable cost is the cost element affected by the level setting of the product attributes and can be expressed as follows:

$$c_p^{var} = \sum_{k=1}^{K} \sum_{l=1}^{L_k} x_{pkl} c_{pkl}$$

$$\sum_{l=1}^{L_k} x_{pkl} = 1$$

where x_{pkl} is the binary variable and equal to 1 if the p-th new product has the l-th level of the k-th attribute and 0 otherwise and c_{pkl} is the cost assigned to the l-th level of the k-th attribute of the p-th new product. Eq. (5) ensures that only one level from each product attribute is selected.

Chain retailers incur two cost components for new products sales: the wholesale cost of new products (p_{pw}) and retailing cost (c_p^R). Retailing cost is the sum of the overhead, operation, and marketing costs subjected to chain retailers.

The cost of producing remanufactured products (c_r^T) mainly consists of the take-back, remanufacturing, and component change costs. The take-back cost (c_r^{tb}) is the sum of the average costs of collecting used products from customers and transportation cost. The remanufacturing cost (c_r^r) is the sum of the average costs of disassembling, inspecting, reconditioning, cleaning, assembling some modules and/or components, and testing the reused products. The cost of component change (c_r^{ch}) is the cost associated with the change of components because of product downgrade or upgrade and replacment of unsatisfactory components with new ones. The OEM must pay the remanufacturer for remanufactured products and must also bear other operational costs (c_r^M), such as transportation, holding, overhead, and remarketing costs.

2.4. Formulation of a multiobjective optimization model for the first period

The profit functions of both OEM and chain retailers and the reaction function of the chain retailers must first be constituted to formulate a multiobjective optimization model in the first period. The unit profit of the OEM from the *p*-th new product can be estimated by subtracting the total cost of developing the *p*-th new product from the wholesale price of the corresponding new product. The market demand of the *p*-th new product in the *i*-th segment can be estimated by multiplying the market share of the *p*-th new product in the *i*-th segment and market potential of the corresponding segment in the first market. Hence, the profit of the OEM from new product sales can be estimated using Eq. (6):

$$\pi_{ip}^{M} = \left[p_{pw} - \left(c_p^f + c_p^v\right)\right] Q_i MS_{ip}$$

where π_{ip}^{M} is the profit of the OEM from the *p*-th new product sales in the *i*-th segment; p_{pw} is the wholesale price of the *p*-th new product; Q_i is the estimated market potential of the *i*-th segment in the first market; and MS_{ip} is the market share of the *p*-th new product in the *i*-th segment.

The unit profit of the chain retailers from the *p*-th new product can be estimated by subtracting the wholesale price of the *p*-th new product from the retail price of the corresponding new product. The profit of the chain retailers from new product sales in the first period can be formulated as follows:

$$\pi_{ip}^{R} = \left[p_{pr} - p_{pw} - c_p^R\right] Q_i MS_{ip}$$

where π_{ip}^{R} is the profit of the chain retailers from the *p*-th new product sales in the *i*-th segment, and p_{pr} is the retail price of the *p*-th new product.

Therefore, the reaction function of the chain retailers, which is the first-order conditions (FOCs) of Eq. (7), can be derived as follows:

$$\frac{\partial \pi_{ip}^{R}}{\partial p_{pr}} = \frac{e^{U_{ip}}}{\sum_{j=1}^{J} e^{U_{ij}} + e^{U_{ip}}} + \left(p_{pr} - p_{pw} - c_p^R\right)\left[\frac{e^{U_{ip}}\left(\sum_{j=1}^{J} e^{U_{ij}}\right)\left(a_{i1} + 2a_{i2}p_{pr}\right)}{\left(e^{U_{ip}} + \sum_{j=1}^{J} e^{U_{ij}}\right)^2}\right] = 0 \qquad (8)$$

The second derivative of the profit function of the chain retailers can be obtained as follows:

$$\frac{\partial^2 \pi_{ip}^R}{\partial {p_{pr}}^2} = \frac{(e^{U_{ip}})(\sum_{j=1}^{J} e^{U_{ij}})\left(a_{i1} + 2a_{i2}p_{pr}\right)}{\left(e^{U_{ip}} + \sum_{j=1}^{J} e^{U_{ij}}\right)^2} + \left[\frac{e^{U_{ip}}\left(\sum_{j=1}^{J} e^{U_{ij}}\right)\left(a_{i1} + 2a_{i2}p_{pr}\right)}{\left(e^{U_{ip}} + \sum_{j=1}^{J} e^{U_{ij}}\right)^2} - \left(p_{pr} - p_{pw} - c_p^R\right)\left[\frac{(\sum_{j=1}^{J} e^{U_{ij}})(e^{U_{ip}})\left(\left(a_{i1} + 2a_{i2}p_{pr}\right)^2 + 2a_{i2}\right)}{\left(e^{U_{ip}} + \sum_{j=1}^{J} e^{U_{ij}}\right)^4}\right]\right] \quad (9)$$

The term $a_{i1} + 2a_{i2}p_{pr}$, which denotes the first derivatives of the utility functions of prices in different markets, must be negative because $e^{U_{ip}}$ and $\sum_{j=1}^{J} e^{U_{ij}}$ are positive terms. We assume that the utility functions of prices are decreasing; hence, the first derivatives of the utility functions of prices are negative. Thus, $\frac{\partial^2 \pi_{ip}^R}{\partial {p_{pr}}^2} < 0$, which proves the existence of a Stackelberg equilibrium point in the first period.

The multiobjective optimization problem in the first period is formulated to determine the Pareto optimal PLD solutions of new product(s) by maximizing the total market share and profit of the product line. Decision variables involve the number and specifications of new product(s) and the wholesale and retail prices of new product(s). Two objective functions are involved in the optimization. The first objective function maximizes the total market share of the product line in the first period (Obj_1^1), which is formulated by dividing the sum of the total demand for new product(s) by the sum of the market potential of individual segments of the first market. The following equation gives the first objective function:

$$\mathrm{Obj}_1^1 = \frac{\sum_{i=1}^{I}\sum_{p=1}^{P} Q_i MS_{ip}}{\sum_{i=1}^{I} Q_i}$$

The second objective function maximizes the total profit of the OEM from the new products (Obj_2^1), as shown in Eq.(11), which can be estimated from the sum of the profits of the OEM from new product(s) in individual segments of the first market.

$$\mathrm{Obj}_2^1 = \sum_{i=1}^{I}\sum_{p=1}^{P} \pi_{ip}^M$$

2.5. Formulation of a multiobjective optimization model for the second period

The profit functions of both the OEM and remanufacturer need to be constituted, and the reaction function of the remanufacturer derived to formulate a multiobjective optimization model for the second period.

The unit profit of the OEM from the *r*-th remanufactured product can be estimated by subtracting the wholesale price of the *r*-th remanufactured product from its selling price. The market demand of the *r*-th remanufactured product in the *z*-th segment can be estimated by multiplying the market share of the *r*-th remanufactured product in the *z*-th segment with the market potential of the corresponding segment in the second market. Hence, the profit of the OEM from the remanufactured products in the second period can be estimated using Eq. (12):

$$\pi_{zr}^{M} = [p_{rs} - p_{rw} - c_r^{M}]Q_z MS_{zr}$$

where π_{zr}^{M} is the profit of the OEM from the *r*-th remanufactured product in the *z*-th segment; p_{rs} is the selling price of the *r*-th remanufactured product which is determined by the OEM; p_{rw} is the wholesale price of the *r*-th remanufactured product, which is determined by the remanufacturer; Q_z is the market potential of the remanufactured products in the *z*-th segment; and MS_{zr} is the market share of the *r*-th remanufactured product in the *z*-th segment.

The unit profit of the remanufacturer from the *r*-th remanufactured product can be estimated by subtracting the total cost of developing the *r*-th remanufactured product from the wholesale price of the corresponding remanufactured product. The profit of the remanufacturer from the remanufactured products can be estimated using Eq.(13):

$$\pi_{zr}^{R} = [p_{rw} - (c_r^{tb} + c_r^{r} + c_r^{ch})]Q_z MS_{zr}$$

where π_{zr}^{R} is the profit of the remanufacturer from the *r*-th remanufactured product in the *z*-th segment.

Therefore, the reaction function of the remanufacturer, FOCs of Eq. (13), can be derived as follows:

$$\frac{\partial \pi_{zr}^{R}}{\partial p_{rw}} = \frac{e^{U_{zr}}}{\sum_{j=1}^{J} e^{U_{zj}} + e^{U_{zr}}} + [p_{rw} - c_r^{T}]\left[\frac{e^{U_{zr}}\left(\sum_{j=1}^{J} e^{U_{zj}}\right)(a_{z1} + 2a_{z2}p_{rw})}{\left(e^{U_{zr}} + \sum_{j=1}^{J} e^{U_{zj}}\right)^2}\right] = 0 \qquad (14)$$

where U_{zr} is the utility of the *r*-th remanufactured product in segment *z*; U_{zj} is the utility of the *j*-th competitive product in segment *z*; and a_{z1} and a_{z2} are the coefficients of the utility functions of price in the *z*-th segment.

The second derivative of the remanufacturer's profit function can be obtained as follows:

$$\frac{\partial^2 \pi_{zr}^R}{\partial {p_{rw}}^2} = \frac{(e^{U_{zr}})(\sum_{j=1}^{J} e^{U_{zj}})(a_{z1} + 2a_{z2}p_{rw})}{\left(e^{U_{zr}} + \sum_{j=1}^{J} e^{U_{zj}}\right)^2} + \left[\frac{e^{U_{zr}}\left(\sum_{j=1}^{J} e^{U_{zj}}\right)(a_{z1} + 2a_{z2}p_{rw})}{\left(e^{U_{zr}} + \sum_{j=1}^{J} e^{U_{zj}}\right)^2} - (p_{rw} - c_r^T)\left[\frac{\left(\sum_{j=1}^{J} e^{U_{zj}}\right)(e^{U_{zr}})((a_{z1} + 2a_{z2}p_{rw})^2 + 2a_{z2})}{\left(e^{U_{zr}} + \sum_{j=1}^{J} e^{U_{zj}}\right)^4}\right]\right] \quad (15)$$

The term $a_{z1} + 2a_{z2}p_{rw}$, denotes the first derivatives of the utility functions of prices in different markets. We assume that the utility functions of prices are decreasing. Hence, the first derivatives of the utility functions of prices are negative. Thus, we obtain $\frac{\partial^2 \pi_{zr}^R}{\partial {p_{rw}}^2} < 0$, which indicates the existence of a Stackelberg equilibrium point in the second period.

Two objective functions are involved in the formulation of the multiobjective optimization model. The first objective function aims to maximize the total market share of the product line in the second period (Obj_1^2), which is formulated as follows:

$$\mathrm{Obj}_1^2 = \frac{\sum_{z=1}^{Z} \sum_{r=1}^{R} Q_z MS_{zr}}{\sum_{z=1}^{Z} Q_z}$$

The second objective function aims to maximize the total profit of the OEM obtained from the remanufactured products (Obj_2^2), which can be expressed as follows:

$$\mathrm{Obj}_2^2 = \sum_{z=1}^{Z} \sum_{r=1}^{R} \pi_{zr}^M$$

In addition, the following constraint ensures that the total demand of the remanufactured product(s) in the second period is less than the volume of the collected products that can be remanufactured in the first periods.

$$\sum_{z=1}^{Z} \sum_{r=1}^{R} Q_z MS_{zr} \leq \delta_r \phi_r \sum_{i=1}^{I} \sum_{p=1}^{P} Q_i MS_{ip}$$

where δ_r is the product return rate and ϕ_r is the remanufacturability rate.

After solving the optimization model using NSGA II, the Pareto optimal PLD solutions of the remanufactured product(s) can be obtained. They include the number and specifications of the remanufactured product(s), wholesale and selling prices of the remanufactured product(s), and product return rate.

3. Case Study

The proposed methodology was applied to the PLD of tablet PCs, which includes both remanufactured and new products, and the CLSC, which involves a manufacturer, chain retailers, and remanufacturer. Table 1 shows eight important product attributes and their corresponding levels defined based on market information.

Table 1. Product attributes and attribute levels of tablet PCs

Index	Attributes	Attribute levels
1	Product condition	New/ remanufactured
2	Screen size	7/10 in
3	Hard disk	16/32/64 GB
4	Memory (RAM)	512 MB/1 GB/2 GB
5	CPU (Processor)	1/1.4/1.6 GHz
6	Screen resolution	1024×768/1280×800/2048×1536
7	Connectivity	Wi-Fi/Wi-Fi + 3G/Wi-Fi + 4G
8	Price	250/450/700 USD

A conjoint survey was conducted to reveal the consumer preferences on tablet PCs based on the defined attributes and attribute levels shown in Table 1. Once the survey data were collected from the first and second markets, a K-means clustering technique based on the SPSS software package was employed to identify the consumer segments for individual markets. In this case study, three segments were identified for the first market, and two segments for the second market. A dummy variable regression method was used to generate the utility functions. Each product attribute consists of dummy variables for the attribute levels. If an attribute has k_i levels, it is coded in terms of $k_i - 1$ dummy variables. The value of a dummy variable is either 1 or 0. For example, the levels of product condition, and hard disk are coded as follows:

Product condition	x_1	Hard disk	x_{31}	x_{32}
New	1	16 GB	1	0
Remanufactured	0	32 GB	0	1
		64 GB	0	0

After the product profiles were coded with the dummy variables, multiple regression analysis was conducted to estimate the coefficients of the utility functions for the first and second markets (Table 2).

Table 2. Coefficients of the utility functions for the first and second markets

Market	Seg.	x_1	x_2	x_{31}	x_{32}	x_{41}	x_{42}	x_{51}	x_{52}	x_{61}	x_{62}	x_{71}	x_{72}	x_{81}	x_{82}	Regr. const.
First	1	0.67	0.17	-0.30	-0.09	-0.48	-0.09	-0.10	-0.04	-0.39	-0.40	-0.58	-0.17	0.99	0.66	3.07
	2	0.48	-0.26	-0.19	-0.53	-0.33	-0.31	-0.03	0.39	-0.44	-0.19	-1.08	-0.31	0.25	0.12	3.44
	3	0.48	0.07	-0.43	-0.14	-0.62	-0.13	-0.44	0.01	-0.29	-0.18	-0.14	-0.07	2.13	1.01	2.21
Second	1	-0.25	0.46	-0.04	0	-1.38	-0.04	0.25	-0.04	-0.21	-0.46	-0.46	-0.33	0.58	0.42	3.71
	2	-0.35	0.10	-0.11	0.13	-0.21	-0.32	-0.08	-0.11	-0.13	0.01	-0.64	-0.10	1.33	0.64	3.08

Note: x_1 is the dummy variable for product condition; x_2 is the dummy variable for screen size; x_{31} and x_{32} are the dummy variables for hard disk; x_{41} and x_{42} are the dummy variables for RAM; x_{51} and x_{52} are the dummy variables for dual CPU; x_{61} and x_{62} are the dummy variables for screen resolution; x_{71} and x_{72} are the dummy variables for connectivity; and x_{81} and x_{82} are the dummy variables for price.

To estimate the utility of continuous-value prices, a curve-fitting method was applied to generate the utility functions of the "price" for individual market segments based on the estimated coefficients of x_{81} and x_{82}. The results are shown as follows:

$$f_{1p}^{pr} = 1.155 - 1.1 \times 10^{-4} p_{pr} - 2.2 \times 10^{-6} (p_{pr})^2$$
$$f_{2p}^{pr} = 0.455 - 9.14 \times 10^{-4} p_{pr} + 3.78 \times 10^{-7} (p_{pr})^2$$
$$f_{3p}^{pr} = 3.92 - 8.027 \times 10^{-3} p_{pr} + 3.467 \times 10^{-6} (p_{pr})^2$$
$$f_{1r}^{pr} = 0.56 + 5.689 \times 10^{-4} p_{rs} - 1.956 \times 10^{-6} (p_{rs})^2$$
$$f_{2r}^{pr} = 2.415 - 4.834 \times 10^{-3} p_{rs} + 1.978 \times 10^{-6} (p_{rs})^2,$$

where f_{ip}^{pr} is the utility function of price for the *p*-th new product in segment *i*, which is equal to 1, 2, and 3; f_{zr}^{pr} is the utility function of the price for the *r*-th remanufactured product in segment *z*, which is equal to 1 and 2.

In this case study, five major competitive tablet PCs in the first market and seven major competitive tablet PCs in the second market were identified. Their specifications and prices are listed in Tables B.1 and B.2 of Appendix B, respectively. The market potentials of the individual segments for the first and second markets were estimated by the marketing staff, as shown in Table 3.

Table 3. Market potentials for the first and second markets

Segment	Market potential for the first market	Market potential for the second market
1	50 000	5 000
2	20 000	15 000
3	30 000	N/A

Total	100 000	20 000

4. Implementation Results

The multiobjective optimization problems for the first period was formulated and coded with Matlab software and solved through the NSGA-II algorithm to determine the product line solutions of new tablet PCs. Deb et al. (2002) introduced the NSGA-II algorithm to furnish a diversified solution set. It has been successfully applied to solve various multiobjective optimization problems, such as PLD (Kwong et al., 2011), integrated PLD and supplier selection (Deng et al., 2014), and product platform design (Wei et al., 2009). Details of NSGA-II are provided in Appendix A.

In this study, the population size of the NSGA-II was set as 100, and the maximum number of generation was set as 1000. Fig. 3 shows the Pareto optimal solutions of the multiobjective optimization problem for the PLD of new tablet PCs.

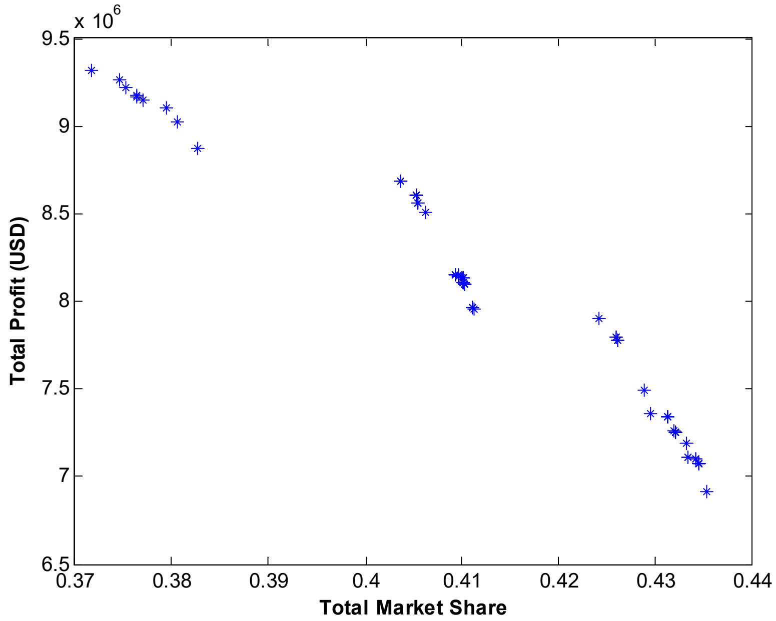

Fig. 3. Pareto solutions for the PLD of new tablet PCs.

The total profit of the OEM obtained from the PLD of new tablet PCs ranges from USD 6.9×10^6 to 9.3×10^6 depending on the total market share of the PLD they would like to obtain. Fig. 4 shows the estimated profits of the chain retailers that ranges from USD 2.5×10^6 to 4.8×10^6, according to the OEM decisions. The total profit of the chain retailers increases as the total market share increases because the profits of the chain retailers increase as retail prices decrease, thereby leading to higher market share with reference to the reaction functions of the chain retailers. Figs. 5 and 6 illustrate the changes of the fitness values of the first and second objective functions over 1000 generations, respectively. From the figures, the maximum profit and maximum market share from the PLD of new tablet PCs are obtained around the 910th and 975th generations, respectively.

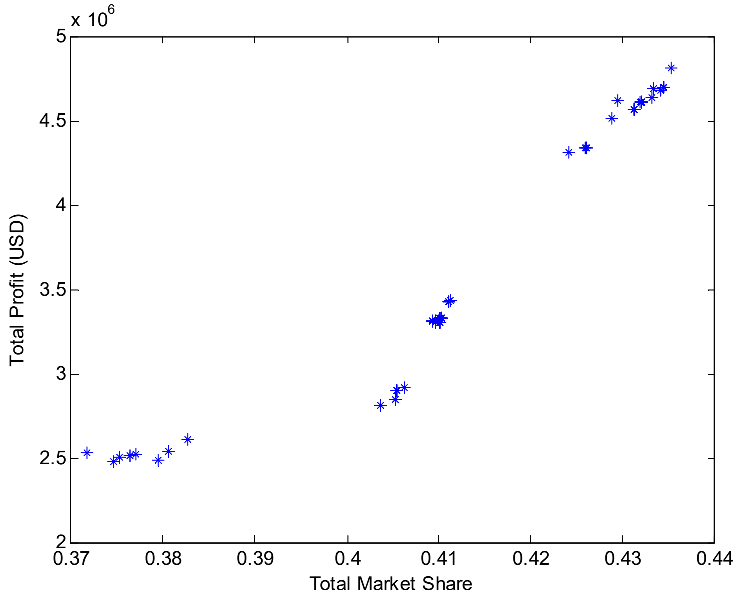

Fig. 4. Estimated profits of the chain retailers from PLD of new tablet PCs.

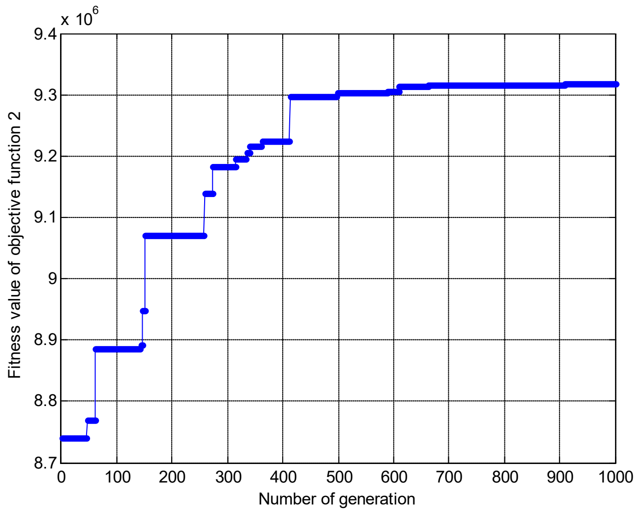

Fig. 5. Solution change in objective function 1.

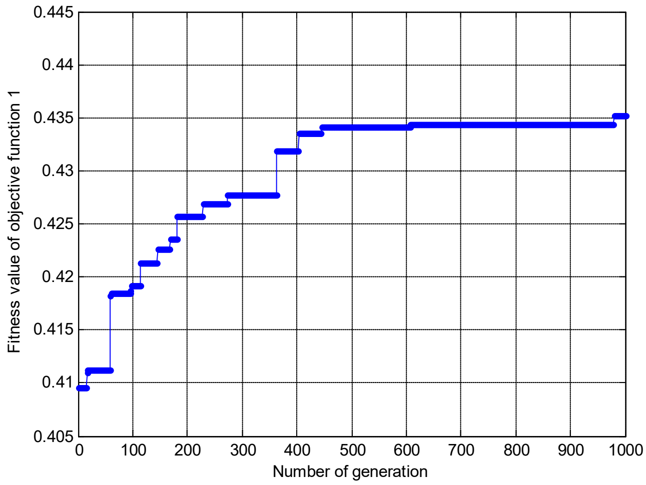

Fig. 6. Solution change in objective function 2.

In simultaneously considering various objectives for a PLD, the objectives may be conflict with one another. Therefore, companies need to perform a tradeoff among various objectives. In the first period, the Pareto optimal solutions are generated for the PLD of new tablet PCs. To obtain the Pareto optimal solutions for the PLD of remanufactured tablet PCs, the company can compare the solutions in the first period, perform a tradeoff between the two objectives, and select the best one with reference to their goals and business strategy. In the following, two product line solutions are presented under two scenarios: maximum profit and maximum market share.

4.1. Maximum profit scenario of OEM

Table 4 shows a product line solution for new tablet PCs that leads to the maximum profit of product line. The product line contains three new products. The estimated profit of the OEM and the total market share of the product line are USD 9.3×10^6 and 37.2%, respectively. The estimated total profit of the chain retailers is USD 2.5×10^6.

Table 4. Product line solution of new tablet PCs for the maximum profit scenario

Product	Screen Size	Hard Disk	Memory	Dual CPU	Screen Resolution	Connectivity	Wholes Price ($)	Retail Price ($)
New Product 1	10 in	32 GB	2 GB	1.4 GHz	2048×1536	Wi-Fi + 3G	531	641
New Product 2	10 in	32 GB	1 GB	1.6 GHz	1280×800	Wi-Fi + 3G	499	580
New Product 3	7 in	32 GB	2 GB	1.4 GHz	1280×800	Wi-Fi	350	448

After obtaining the product line solution for the PLD of new tablet PCs, the PLD of remanufactured tablet PCs based on the maximum profit scenario was then obtained by solving another multiobjective optimization problem. Fig. 7 shows the Pareto optimal solutions for the PLD of remanufactured tablet PCs based on the maximum profit scenario of the OEM.

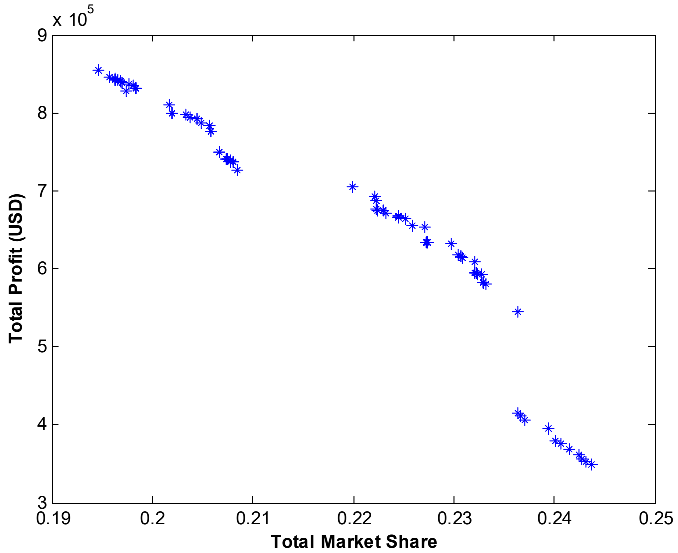

Fig. 7. Pareto solutions for the PLD of remanufactured tablet PCs for the maximum profit scenario.

Fig. 7 shows that the estimated total profits of the OEM from the PLD of remanufactured tablet PCs range from USD 3.5×10^5 to 8.5×10^5, whereas the estimated total market shares of the PLD of remanufactured tablet PCs range from 19.5% to 24.4%. Fig. 8 shows that the estimated profits of the remanufacturer range from USD 4.9×10^5 to 9.9×10^5. The total profit of the remanufacturer increases as the market share increases because the remanufacturer increases the wholesale prices as selling prices decrease based on the reaction function.

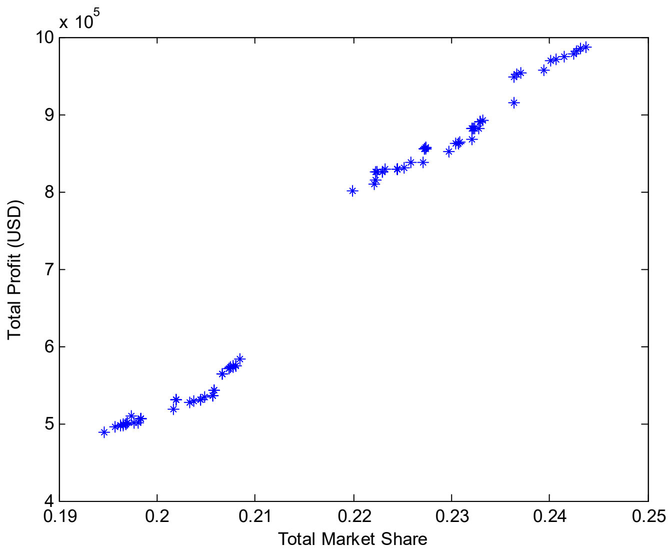

Fig. 8. Estimated profits of the remanufacturer for the maximum profit scenario.

Table 5 shows a product line solution of remanufactured tablet PCs, which leads to the maximum profit of the product line. The product line contains two remanufactured products. The estimated maximum profit of the OEM and the total market share of the product line are USD 8.5×10^5 and 19.5%, respectively. The estimated total profit of the remanufacturer is USD 4.9×10^5, and the product return rate is 0.15.

Table 5. Product line solution of remanufactured tablet PCs for the maximum profit scenario

Product	Screen Size	Hard Disk	Memory	Dual CPU	Screen Resolution	Connectivity	Wholes Price ($)	Selling Price ($)
Remanufactured Product 1	10 in	32 GB	1 GB	1.6 GHz	1280×800	Wi-Fi + 3G	256	490
Remanufactured Product 2	7 in	32 GB	512 MB	1.4 GHz	1024×768	Wi-Fi + 3G	150	396

4.2. Maximum market share scenario of OEM

A product line solution for new tablet PCs based on the maximum market share scenario was generated, as shown in Table 6. The product line contains three new products. The estimated profit and the total market share of the product line are USD 6.9×10^6 and 43.5%, respectively. The estimated total profit of the chain retailers is USD 4.8×10^6.

Table 6. Product line solution of new tablet PCs for the maximum market share scenario

Product	Screen Size	Hard Disk	Memory	Dual CPU	Screen Resolution	Connectivity	Wholes Price ($)	Retail Price ($)
New Product 1	10 in	64 GB	2 GB	1.4 GHz	2048×1536	Wi-Fi + 3G	491	666
New Product 2	10 in	32 GB	2 GB	1.6 GHz	1024×768	Wi-Fi + 4G	337	485
New Product 3	7 in	32 GB	1 GB	1 GHz	1280×800	Wi-Fi + 3G	285	373

The product line solutions of new tablet PCs based on the maximum market share scenario above were adopted as inputs to the multiobjective optimization model for the second period. Fig. 9 shows the Pareto optimal solutions for the PLD of remanufactured tablet PCs based on the maximum market share scenario of the OEM.

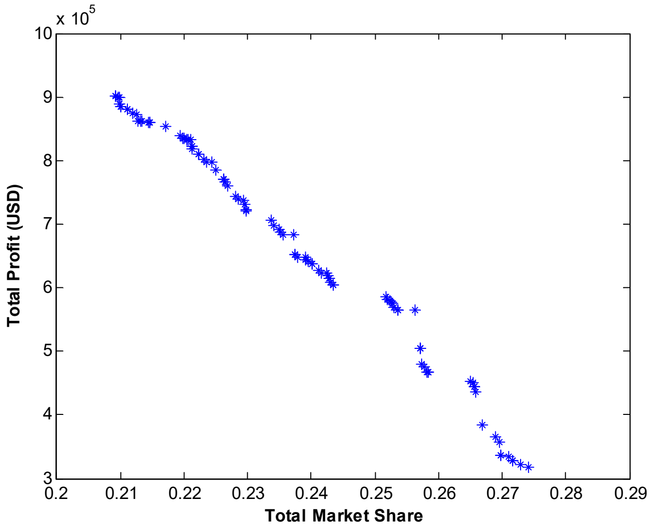

Fig. 9. Pareto solutions for PLD of remanufactured tablet PCs for maximum market share scenario.

Fig. 9 shows that the estimated total profit of the OEM obtained from the PLD of remanufactured tablet PCs ranges from USD 3.2×10^5 to 9×10^5, whereas the estimated total market share of the PLD of remanufactured tablet PCs ranges from 20.9% to 27.4%. Fig. 10 shows that the estimated profits of the remanufacturer range from USD 5.4×10^5 to 11.9×10^5.

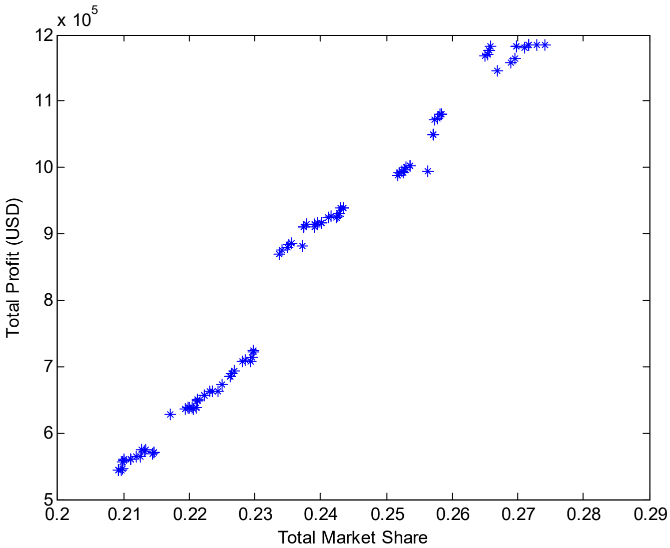

Fig. 10. Estimated profits of the remanufacturer for the maximum market share scenario.

Table 8 shows a product line solution of remanufactured tablet PCs, which leads to the maximum market share of the product line. The product line contains two remanufactured products. The estimated profit of the OEM and the total market share of the product line are USD 3.2×10^5 and 27.4%, respectively. The estimated total profit of the remanufacturer is USD 11.9×10^5, and the product return rate is 0.18.

Table 8. Product line solution of remanufactured tablet PCs for the maximum market share scenario

Product	Screen Size	Hard Disk	Memory	Dual CPU	Screen Resolution	Connectivity	Wholes Price ($)	Selling Price ($)
Remanufactured Product 1	10 in	32 GB	512 MB	1 GHz	2048×1536	Wi-Fi + 4G	300	382
Remanufactured Product 2	7 in	64 GB	2 GB	1.4 GHz	1280×800	Wi-Fi + 4G	279	353

5. Discussion

Both researchers and companies can adopt the proposed methodology to determine product line solutions that involves both new and remanufactured products, pricing decisions of supply chain parties and product return rate for remanufacturing. The PLD under the two distinct scenarios of maximum profit and maximum market share were examined. In the first period, the OEM obtains much higher profit than the chain retailers for both the maximum profit and maximum market share scenario. In the maximum market share scenario, the OEM's profit generated from the new products decreases by 25.8% while their market share increases by 16.9% compared to those in the maximum profit scenario. However, the total profit of the chain retailers increases as the market share increases. Both the retail and wholesale prices of new tablet PCs are lower in the maximum market share scenario than those in the maximum profit scenario because the reduction of the retail prices of new tablet PCs makes the new tablet PCs attractive in markets, thereby increasing the market share of tablet PCs. On the other hand, it can be noted that specifications of the new tablet PCs in the maximum market share scenario are better than those in the maximum profit scenario. In the second period, the profits of the OEM and total market share obtained from the PLD of remanufactured tablet PCs for both maximum profit and market share scenarios are very close because of the availability of product returns and considerable demand in the second market. In the maximum market share scenario, the OEM's profit obtained from remanufactured products decreases by 62.3% while their market share increases by 40.5% compared to those in the maximum profit scenario. However, the remanufacturer gains a much higher profit under the maximum market share scenario than under the maximum profit scenario. These results indicate that both chain retailers and remanufacturer are stronger in the game for the maximum market share scenario than that for the maximum profit scenario. OEM needs to increase pay-off to the chain retailers and remanufacturer if he would like to increase market share of its products. Since the model was developed based on the OEM's perspective, the tradeoff between the two objectives, maximizing market share and maximizing profit, can only be performed for the OEM.

In view of the industrial practice in new product development, companies are required to perform a tradeoff among various objectives and select the best/most preferred one with reference to their business objectives and competitive strategies. Since NSGA-II cannot guarantee that the obtained non-dominant solutions are Pareto ones, companies could establish some rules and/or guidelines for each new product development project such that the rules and/or guidelines could be used to help them select their most desirable solutions.

The product return rate depends on a number of parameters, such as the market potential of both the first and second markets, remanufacturability rate, and the production capacity of the remanufacturer. In this case study, the production capacity of the remanufacturer is assumed to be adequate to produce the required quantities of remanufactured products. Therefore, the product return rate may need to be increased to satisfy the demand of the second market and improve the profits of both the OEM and remanufacturer, whereas the remanufacturability rate decreases and/or the market potential of the second market increases.

6. Conclusions and future work

This study proposes a methodology for the coordination of a manufacturer, chain retailers, and a remanufacturer to undertake PLD with consideration of remanufactured products to maximize the profit and market share of product lines. The methodology addresses the relationship between product returns and demand of remanufactured products and determines the return rate of new products. The methodology mainly involves conjoint analysis, generation of choice models, Stackelberg game theoretical approach, formulation of multiobjective optimization problems, and solving the multiobjective optimization problems by NSGA-II. Two multiobjective optimization models are established for the first and second periods through Stackelberg game theory approach. Solving the optimization models determines the product line solutions for the new and remanufactured products, estimated total profits and market shares of the product lines, wholesale and retail prices of new products, wholesale and selling prices of remanufactured products, and product return rate. A case study was conducted on the coordination of a manufacturer and supply chain partners for the PLD of tablet PCs with consideration of remanufactured tablet PCs to evaluate the effectiveness of the proposed methodology. The main contribution of this study is to model the coordination of an OEM and supply chain parties for PLD that involves both new and remanufactured products in competitive markets in which market demands are estimated based on both product design and price.

In this research, the two-period static game model was developed for the coordination of CLSC for PLD. A dynamic model can be established in the future to determine the time of launching remanufactured products in markets and the periodic quantity of product returns. The new and remanufactured products are discretely launched in the first and second markets, respectively. The launch of remanufactured products in the first market can be considered in future work to examine the competition between new and remanufactured products. This study can be extended by considering multiple supply chain parties in the coordination model.

On the other hand, in this study, the product return rate is estimated based on the relationship between product returns and demand for remanufactured products as well as remanufacturability of returned products. However, a more sophisticated model could be developed to estimate product return rate with consideration of the relationship between new product sales and product returns.

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Appendix A. Flowchart and details of NSGA II

NSGA-II adopts fast nondominated sorting approach and crowded comparison without any need for user-defined parameters. This algorithm is highly capable of reducing computational time and providing a fast and effective constraint-handling strategy. A flowchart of NSGA-II is shown in Fig. A.1.

The rank and crowded distance are used as a binary tournament selection process to select parent chromosomes for the mating pool in NSGA-II. The size of the mating pool is commonly equal to one half of the population size. Once adequate parents are selected for the mating pool, crossover and mutation operators are performed to generate the child chromosomes. Real-coded GA, which uses simulated binary crossover (SBX) and polynomial mutation (Deb and Agarwal, 1995), is adopted in this study. Crossover refers to the exchange of the genes between randomly selected parent chromosomes from the mating pool, in which excellent fitness value chromosomes can possibly be generated. The crossover probability, pc, is set as 0.9. Mutation refers to the change in the value of randomly selected genes to search for a better fitness value for each population. Mutation probability, pm, is set as 1/n, where n is the number of decision variables. Two child chromosomes are generated through crossover, but only one child is generated through mutation. When both crossover and mutation operations are completed, the fitness values are calculated; the chromosomes with better fitness values are selected for the solution of the population. After the maximum number of generation is reached, NSGA-II operations are terminated.

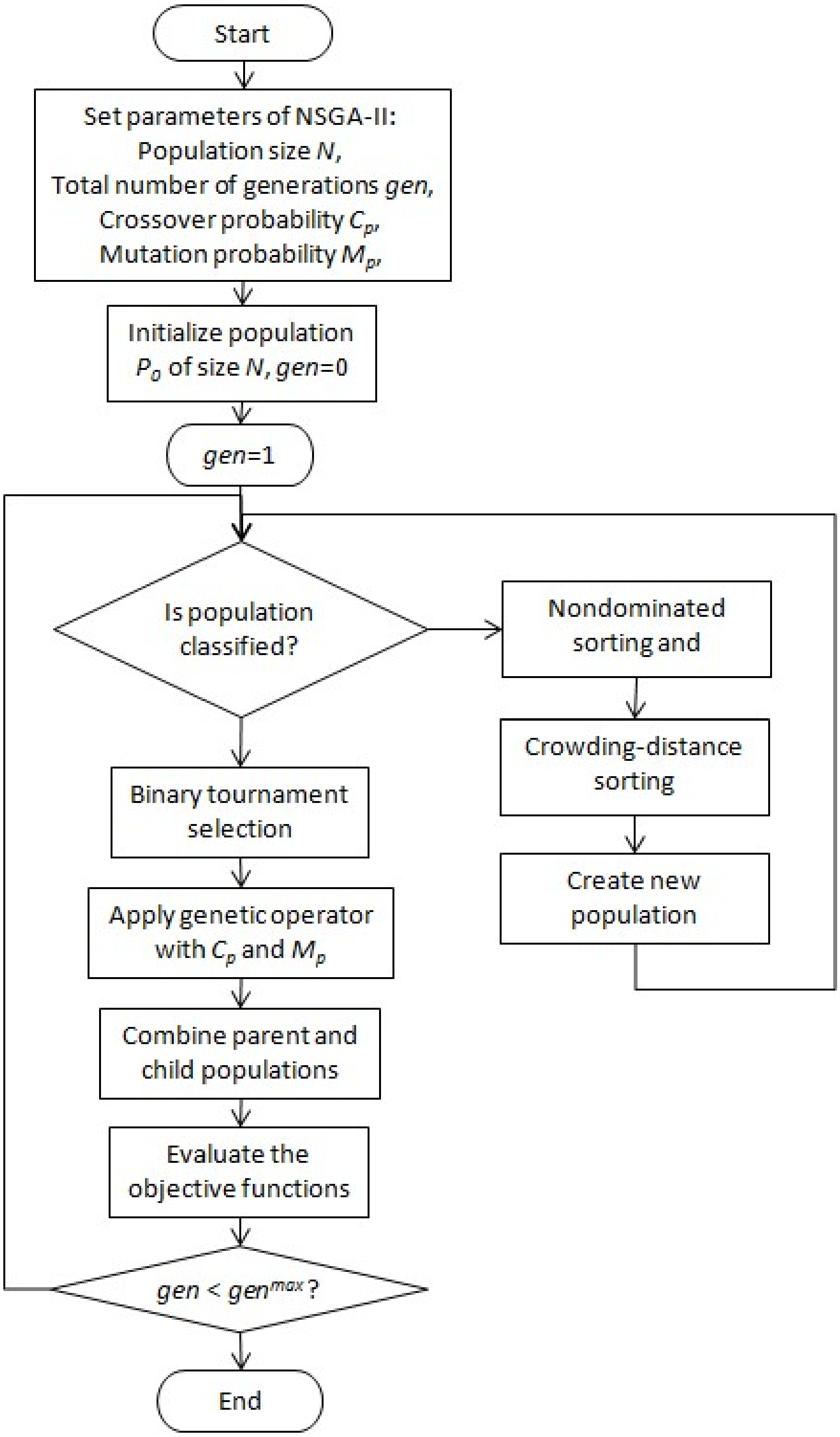

Fig. A.1 Flowchart of NSGA-II

Appendix B. Specifications and prices of competitive tablet PCs in markets

Table B.1 Specifications and prices of competitive tablet PCs in the first market

Product	Screen Size	Hard Disk	Memory	Dual CPU	Screen Resolution	Connectivity	Price (USD)
Product A	10 in	16 GB	2 GB	1.4 GHz	1280×800	Wi-Fi + 3G	510
Product B	10 in	32 GB	2 GB	1.6 GHz	2048×1536	Wi-Fi	440
Product C	7 in	16 GB	2 GB	1.6 GHz	1280×800	Wi-Fi	320
Product D	7 in	16 GB	512 MB	1 GHz	1024×768	Wi-Fi + 3G	450
Product E	10 in	32 GB	1 GB	1.4 GHz	2048×1536	Wi-Fi + 4G	700

Table B.2 Specifications and prices of competitive tablet PCs in the second market

Product	Screen Size	Hard Disk	Memory	Dual CPU	Screen Resolution	Connectivity	Price (USD)
Product F	10 in	16 GB	2 GB	1.4 GHz	1280×800	Wi-Fi	340
Product G	10 in	16 GB	1 GB	1 GHz	1280×800	Wi-Fi	260
Product H	10 in	16 GB	1 GB	1 GHz	1280×800	Wi-Fi	160
Product I	10 in	64 GB	1 GB	1 GHz	1024×768	Wi-Fi + 3G	500
Product J	7 in	32 GB	1 GB	1 GHz	1280×800	Wi-Fi	155
Product K	10 in	32 GB	1 GB	1.4 GHz	2048×1536	Wi-Fi + 4G	500
Product L	7 in	16 GB	512 MB	1 GHz	1024×768	Wi-Fi + 3G	360