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Coordination of a manufacturer and supply chain partners for product line design with consideration of remanufactured products

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Abstract

The coordination among supply chain partners for product line design (PLD) with consideration of remanufactured products has not been addressed in previous studies. This study aims at studying the coordination among a manufacturer, and supply chain partners using a game theoretical model for design of product lines that contain both new and remanufactured products. A multiobjective optimization model based on Stackelberg game theory is formulated to determine product line solutions, pricing decisions of supply chain partners and the product return rate for remanufacturing. A case study was conducted to illustrate the effectiveness of the proposed methodology.

Keywords: Product line design; closed-loop supply chain; Stackelberg game theory; multiobjective optimization; NSGA-II.

1. Introduction

To satisfy increasingly diversified customer needs, product line design (PLD) has been widely adopted by many companies in developing various product variants. PLD helps increase the profitability and market shares of products, which involves the determination of the number of product variants and their design attribute settings [1]. Some studies have been conducted on the closed-loop supply chain (CLSC) for product design and pricing. A CLSC involves collection of used products from customers, supporting various product recovery strategies, such as remanufacturing, recycling and reuse, and managing the relationship and coordinating with supply chain partners. Various studies on CLSC were conducted, such as evolution of CLSC [2], CLSC network design and coordination among supply chain parties [3], and CLSC models for product collection [4].

There are two common scenarios of remanufacturing. For the first one, remanufacturing is a process in which used products are disassembled, and their parts are repaired and used in the production of new products [5]. Regarding the second one, remanufacturing is treated as a product recovery strategy in which returned products are restored functionally and aesthetically to like-new condition. Only a limited number of studies have considered remanufactured products in the product design stage. Vorasayan and Ryan [6] developed an optimization model to determine product return rate and price of remanufactured products. Ferrer and Swaminathan [5] examined optimal policies for remanufacturing and pricing of new and differentiated remanufactured products in a monopoly market; however, product design was not considered in the estimation of demand of products. Kwak and Kim [7] established a market positioning model for remanufactured products to determine the optimal settings and price of a remanufactured product. Chen and Chang [8] investigated dynamic pricing strategy for new and remanufactured products in a CLSC. All the studies focused on optimal product design and/or pricing of remanufactured products in a centralized case which did not consider other supply chain partners apart from manufacturer.

The competition and coordination among original equipment manufacturer (OEM) and supply chain partners have been studied to determine optimal product design and pricing of new and remanufactured products [9,10] as well as examine product collection for remanufacturing [11,12]. Wu [13,14] developed game models to investigate the competition

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between an OEM and remanufacturer for product design and pricing decisions of new and remanufactured products.

However, the coordination for PLD that involves both new and remanufactured products in competitive markets where demands are estimated based on product design and price has not been addressed in previous studies. In this paper, a methodology for the coordination of a manufacturer, chain retailers, and remanufacturer to undertake PLD that involves remanufactured products is proposed by which profit and market share of the product line can be maximized. The proposed methodology can provide optimal solution for the product component set in simultaneously considering new and remanufactured products of PLD, pricing decisions of supply chain parties and product return rate for remanufacturing. The relationship between product returns and demand for remanufactured products is addressed and the return rate of new products is determined.

2. Proposed methodology

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

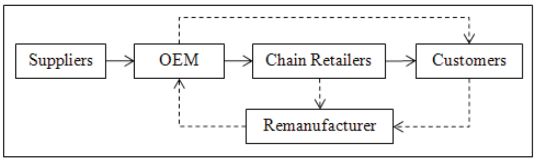

Fig. 1. Closed-loop supply chain.

Two types of markets are considered in this research, 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 type is normally a relatively less developed market where consumers generally may unable to afford brand new products but they may be interested in lower-priced remanufactured products. New products are launched in the first market, whereas remanufactured products are launched in the second market. Since new and remanufactured products are launched at different times, two periods are specified. In the first period, new products are produced by the OEM and sold to customers by chain retailers. In the second period, the remanufacturer collects used or defected products, and refurbishes the collected products by changing some components, and reconditioning. 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 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. Fig. 2 shows the proposed methodology for the first and second periods which mainly involves conjoint analysis, generation of choice models, formulation of Stackelberg game and multiobjective optimization models, and solving the optimization problems using a nondominated sorting genetic algorithm II (NSGA-II). Two common objectives of PLD, maximizing profit and market share, are considered in this research and the tradeoff between the two objectives can be realized by using a multiobjective optimization paradigm. 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 [15].

In the proposed methodology, conjoint analysis is conducted to obtain customer preferences on products in the first and second markets by estimating the part-worth utilities for each level of product attributes [16]. The utility functions of individual segments are thereafter generated using statistical regression. The multinomial logit (MNL) model 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. The OEM and chain retailers compete for the prices of new products in the first period. 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. Pareto optimal PLD solutions for the new products, market shares, and profits of the PLD can also be obtained. In the second 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 based on the remanufacturer's reaction function and determined specifications and on 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.

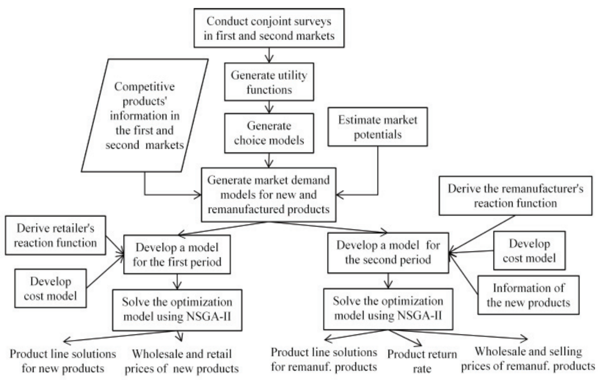

Fig. 2. The proposed methodology.

2.1. Development of market share models

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:

$$f_{ij}^{pr} = a_{i0} + a_{i1}p_j + a_{i2}(p_j)^2 \tag{1}$$

where f_{ij}^{pr} is the utility of the price of the *j*-th product in the *i*-th segment; 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.

In this research, market share models are developed based on the following MNL and generated utility functions:

$$MS_{ip} = \frac{e^{U_{ip}}}{\sum_{j=1}^{J} e^{U_{ij}} + \sum_{k=1}^{K} e^{U_{ik}} + e^{U_{ip}}} \tag{2}$$

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*.

2.2. Development of cost models

The cost model for new product variants is developed based on SIMOPT models [1], 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:

$$c_p^v = \sum_{k=1}^{K}\sum_{l=1}^{L_k} x_{pkl}c_{pkl} \tag{3}$$

$$\sum_{l=1}^{L_k} x_{pkl} = 1 \tag{4}$$

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. (4) ensures that only one level from each product attribute is selected.

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. 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^c) is the cost associated with the change of components because of product downgrade or upgrade and replacement of unsatisfactory components with new ones.

2.3. 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 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. (5):

$$\pi_{Mip}^1 = [p_{pw} - (c_p^f + c_p^v)]Q_iMS_{ip} \tag{5}$$

where π_{Mip}^1 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; and Q_i is the estimated market potential of the *i*-th segment in the first market.

The unit profit of 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 chain retailers from new product sales in the first period can be formulated as follows:

$$\pi_{Rip}^1 = [p_{pr} - p_{pw}]Q_iMS_{ip} \tag{6}$$

where π_{Rip}^1 is the profit of 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 chain retailers, which is the first-order conditions (FOCs) of Eq. (6), can be derived as:

$$\frac{\partial \pi_{Rip}^1}{\partial p_{pr}} = \frac{e^{U_{ip}}}{\sum_{j=1}^{J} e^{U_{ij}} + e^{U_{ip}}} + (p_{pr} - p_{pw})\left[\frac{e^{U_{ip}}\left(\sum_{j=1}^{J} e^{U_{ij}}\right)(a_{i1}+2a_{i2}p_{pr})}{\left(e^{U_{ip}}+\sum_{j=1}^{J} e^{U_{ij}}\right)^2}\right] = 0 \tag{7}$$

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

$$\frac{\partial^2 \pi_{Rip}^1}{\partial {p_{pr}}^2} = \frac{\left(e^{U_{ip}}\right)\left(\sum_{j=1}^{J} e^{U_{ij}}\right)(a_{i1}+2a_{i2}p_{pr})}{\left(e^{U_{ip}}+\sum_{j=1}^{J} e^{U_{ij}}\right)^2} + \frac{e^{U_{ip}}\left(\sum_{j=1}^{J} e^{U_{ij}}\right)(a_{i1}+2a_{i2}p_{pr})}{\left(e^{U_{ip}}+\sum_{j=1}^{J} e^{U_{ij}}\right)^2} - (p_{pr} - p_{pw})\left[\frac{\left(\sum_{j=1}^{J} e^{U_{ij}}\right)\left(e^{U_{ip}}\right)\left((a_{i1}+2a_{i2}p_{pr})^2+2a_{i2}\right)}{\left(e^{U_{ip}}+\sum_{j=1}^{J} e^{U_{ij}}\right)^4}\right] \tag{8}$$

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, $\frac{\partial^2 \pi_{Rip}^1}{\partial {p_{pr}}^2} < 0$, 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). The variables for design specifications are binary variables. The wholesale and retail prices are constrained by setting the lower and upper levels. 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, 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 second objective function maximizes the total profit of the OEM from the new products that can be estimated from the sum of profits of the OEM from new product(s) in individual segments of the first market.

2.4. 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 remanufactured products in the second period can be estimated using Eq. (9):

$$\pi_{Mzr}^2 = [p_{rs} - p_{rw}]Q_z MS_{zr} \tag{9}$$

where π_{Mzr}^2 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 the remanufactured product which is determined by the remanufacturer; Q_z is the market potential of 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.(10):

$$\pi_{Rzr}^2 = [p_{rw} - (c_r^{tb} + c_r^r + c_r^c)]Q_z MS_{zr} \tag{10}$$

where π_{Rzr}^2 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. (10), can be derived as follows:

$$\frac{\partial \pi_{Rzr}^2}{\partial p_{rw}} = \frac{e^{U_{zr}}}{\sum_{j=1}^{J} e^{U_{zj}} + e^{U_{zr}}} + (p_{rw} - c_r^T)\left[\frac{e^{U_{zr}}\left(\sum_{j=1}^{J} e^{U_{zj}}\right)(a_{z1}+2a_{z2}p_{rw})}{\left(e^{U_{zr}}+\sum_{j=1}^{J} e^{U_{zj}}\right)^2}\right] = 0 \tag{11}$$

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

$$\frac{\partial^2 \pi_{Rzr}^1}{\partial {p_{rw}}^2} = \frac{(e^{U_{zr}})(\sum_{j=1}^{J} e^{U_{zj}})(a_{z1}+2a_{z2}p_{rw})}{\left(e^{U_{zr}}+\sum_{j=1}^{J} e^{U_{zj}}\right)^2} + \frac{e^{U_{zr}}\left(\sum_{j=1}^{J} e^{U_{zj}}\right)(a_{z1}+2a_{z2}p_{rw})}{\left(e^{U_{zr}}+\sum_{j=1}^{J} e^{U_{zj}}\right)^2} - (p_{rw} - c_r^T)\left[\frac{\left(\sum_{j=1}^{J} e^{U_{zj}}\right)(e^{U_{zr}})((a_{z1}+2a_{z2}p_{rw})^2+2a_{z2})}{\left(e^{U_{zr}}+\sum_{j=1}^{J} e^{U_{zj}}\right)^4}\right] \tag{12}$$

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 $\frac{\partial^2 \pi_{Rzr}^2}{\partial {p_{rw}}^2} < 0$, 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. The second objective function aims to maximize the total profit of the OEM obtained from the remanufactured products.

Constraints of the variables for remanufactured products are similar with those for new products as described in Section 2.3. 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 period.

$$\sum_{z=1}^{Z} \sum_{r=1}^{R} Q_z MS_{zr} \le \delta_r \phi_r \sum_{i=1}^{I} \sum_{p=1}^{P} Q_i MS_{ip} \tag{13}$$

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

After solving the optimization model using NSGA-II, Pareto optimal PLD solutions of the remanufactured product(s) can be obtained that include the number and specifications of remanufactured product(s), the wholesale and selling prices of remanufactured product(s), and the 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 (ScS)	7/10 in
3	Hard Disk (HrD)	16/32/64 GB
4	Memory (RAM)	512 MB/1 GB/2 GB

5	Processor (CPU)	1/1.4/1.6 GHz
6	Screen Resolution (ScR)	1024×768/1280×800/2048×1536
7	Connectivity (Con)	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. The market potentials of the individual segments for the first and second markets were estimated by the marketing staff.

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. In this study, the population size of the NSGA-II, which refers to a set of solutions or the best individual chromosomes, was set as 100. The maximum number of generation, which refers to a termination condition to stop the algorithm, was set as 1000. Fig. 3 shows the Pareto optimal solutions of the multiobjective optimization problem for the PLD of new tablet PCs. The total profit of the OEM obtained from the PLD of new tablet PCs ranges from USD 5.3 to 9.38 million depending on which value of total market share of the PLD would like to be obtained.

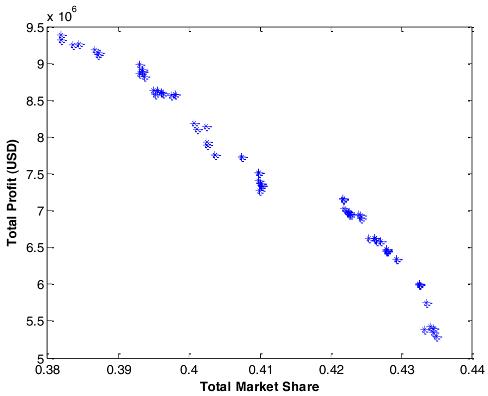

Fig. 3. Pareto solutions for PLD of new tablet PCs.

Fig. 4 shows that the estimated profits of the chain retailers range from USD 3.09 to 6.53 million, 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.

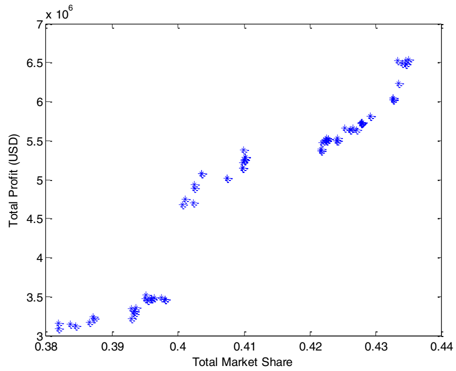

Fig. 4. Estimated profits of the chain retailers.

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 with reference to their goals and business strategy. For illustrative purpose, we present the product line solutions under the maximum profit scenario in the next section.

4.1. Maximum profit scenario of OEM

Table 2 shows a product line solution for new tablet PCs, which 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 9.38 million and 38.2%, respectively. The estimated total profit of the chain retailers is USD 3.09 million.

Table 2. Product line solution of new tablet PCs for the maximum profit.

Prod	ScS	HrD	RAM	CPU	ScR	Con	p_{pw}	p_{pr}
New Prod 1	10 in	32 GB	1 GB	1.6 GHz	2048× 1536	Wi-Fi +4G	596	671
New Prod 2	10 in	32 GB	1 GB	1.6 GHz	1280× 800	Wi-Fi	329	380
New Prod 3	7 in	32 GB	1 GB	1.4 GHz	1024× 768	Wi-Fi +4G	449	569

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 model. Fig. 5 shows the Pareto optimal solutions for the PLD of remanufactured tablet PCs based on the maximum profit scenario of the OEM.

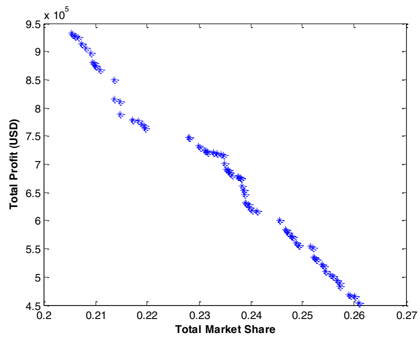

Fig. 5. Pareto solutions for PLD of remanufactured tablet PCs.

Table 3 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 0.93 million and 20.5%, respectively. The estimated total profit of the remanufacturer is USD 0.58 million, and the product return rate is 0.15.

Table 3. Product line solution of remanufactured tablet PCs.

Prod	ScS	HrD	RAM	CPU	ScS	Con	p_{rw}	p_{rs}
Rem Prod 1	10 in	32 GB	1 GB	1.4 GHz	2048× 1536	Wi-Fi +4G	252	500
Rem Prod 2	7 in	32 GB	1 GB	1 GHz	1280× 800	Wi-Fi	154	349

Fig. 6 shows that the estimated total profits of the remanufacturer range from USD 0.58 to 0.84 million. It can be noted that the total profit of the remanufacturer increases as the market share increases. It is because the remanufacturer increases the wholesale prices of remanufactured products even though the selling prices of remanufactured products are decreased based on the reaction function.

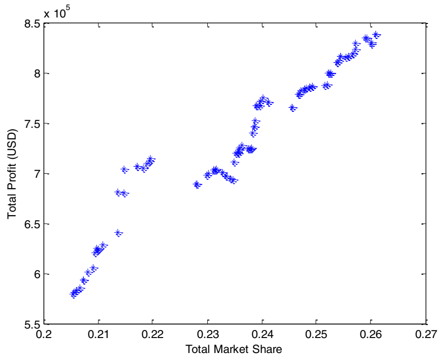

Fig. 6. Estimated profits of the remanufacturer.

5. Conclusion and future work

This study proposes a methodology for the coordination of a manufacturer, chain retailers, and remanufacturer to undertake PLD with consideration of remanufactured products to maximize the profit and market share of product lines. The proposed methodology is able 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 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. MNL models were adopted in this study to develop the demands models which are able to incorporate consumer preferences on market demand estimation. 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 proposed methodology can be applied to any product type which does not monopolize its market. In this case study, the production capacity of both the OEM and remanufacturer is assumed to be adequate to produce the required quantities of new and remanufactured products, respectively. The production capacity constraints would be involved in a real case application in the future. In this research, the two-period static game model was developed for the coordination of CLSC. A dynamic model can be established in the future to determine the time of launching remanufactured products in markets, which would help to determine a product line solution with higher profit and market share.

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