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RESEARCH ARTICLE

Pricing decision model for new and remanufactured short life-cycle products with green consumers

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Abstract

Remanufacturing has been studied quite extensively during the last decades, as one of product recovery options that could extend product's useful life and mitigate the environmental impact. Rapid innovation in technology accelerates obsolescence and hence product life cycles are getting shorter and wastes build up faster. Remanufacturing of short life-cycle product is an important alternative to mitigate the waste. However, since there are impacts in implementing remanufacturing, such as cannibalization, segmentation, and lower willingness to pay, pricing has become a significant aspect to ensure successful remanufacturing business. Several studies show that there exists green segment consumer, who has higher preference to purchase environmental-friendly products and higher willingness to pay for such products. In this paper, we study manufacturer's and retailer's pricing decision of short life-cycle product considering the green segment consumers, and propose two scenarios i.e. independently optimized profit scenario under Stackelberg game with manufacturer as the leader, and integrated scenario. The results show that the integrated scenario achieves higher profit compared to the independent one, and both players are better off under the integrated decision. We also find that the existence of green segment increases the profit of manufacturer and retailer to a certain level, before it erodes manufacturer's profit when the green level is too high. In addition, price sensitivity of new and remanufactured products, demand's speed of change, and remanufacturing cost influence the optimum prices as well as the optimum green level. For firms that are engaging in remanufacturing, managerial insights are also provided to assist managers in making pricing decisions when there exist green consumers.

Keywords Pricing · Remanufacturing · Short life-cycle product · Green consumers

List of notations

Decision variables: All variables are non-negative

- P_n Retail price of the new product
- P_r Retail price of the remanufactured product
- P_{nw} Wholesale price of the new product $P_{nw} \leq P_n$
- P_{rw} Wholesale price of the new product
- θ Green level

Parameters: All parameters are non-negative

- D_n Demand capacity of the new product
- D_r Demand capacity of the remanufactured product
- a New product's price sensitivity, i.e., the sensitivity of the demand for the new product to a change in the price of the new product
- b Remanufactured product's cross-price sensitivity, i.e., the sensitivity of the demand for the new product to a change in the price of the remanufactured product
- c Remanufactured product's price sensitivity, i.e., the sensitivity of the demand for the remanufactured product to a change in the price of the remanufactured product
- e New product's cross-price sensitivity, i.e., the sensitivity of the demand for the remanufactured product to a change in the price of the new product
- λ Speed of change in demand capacity for new product
- η Speed of change in demand capacity for remanufactured product
- c_m Unit manufacturing cost of producing the new product

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c_r Unit remanufacturing cost of producing the remanufactured product
γ Green-level-demand-expansion coefficient
ρ Green-level-investment coefficient
φ Contracted revenue sharing portion

Introduction

With the increasing speed of innovation in technological-based products, new ideas area getting to the market faster and old products are pushed away from the market. The new models of mobile phones, digital camera, LED TV, and many others are reaching the market faster from time to time. While these innovation brings excitement to the consumers, environmental burden are becoming more severe as the old products may have to be wasted faster than technically it should be. On the other hand, the speed of depletion in natural resources is increasing to support the production of these new product generations.

Attempt to slow down the speed of waste build up and the depletion of natural resources has been a hot issue in recent years. Of various alternatives, remanufacturing has been considered as an important way to protect the mother earth from waste build up and fast depletion of natural resources. Remanufacturing is a product recovery process that transforms used products into “like-new” condition. For remanufacturing business to stay competitive, demand should exist and supply of materials in the form of used products should be available in a sufficient amount with adequate quality for remanufacturing process.

Demand for remanufactured products maybe available due to various reasons. There may be a segment of customers who are willing to purchase the remanufactured goods because it is priced cheaper compared to the new ones. Others may prefer to purchase them over the new products because they value the concept of remanufacturing for sustainability reason. Literature has discussed about this green segment recently (see for example Mostafa 2007; Jiménez-Parra et al. 2014; Wang et al. 2018; Chen et al. 2018; Zhou and Gupta 2019; Michaud and Llerena 2011; Finisterra do Paço and Raposo 2010). Few authors consider that remanufactured products is an inferior substitution to the new one (Debo et al. 2005) unless given green image (Michaud and Llerena 2011). Others argue that there are customers who values green or remanufacturable product higher (Abeliotis et al. 2010; Finisterra do Paço and Raposo 2010; Gu et al. 2015) but remanufactured product lower (Gu et al. 2015). All of these suggest that segmenting and pricing of remanufactured products is a critical decision to ensure business continuity.

Research to address pricing decisions for manufactured products have attracted attentions from researchers. Researchers argue that appropriate pricing strategy for remanufactured products avoid cannibalization, expand the market and thus ensure profitability. Guide and Wassenhove (2009), Atasu et al. (2010), Souza (2013) are among the authors who discussed pricing of new and remanufactured products in a closed-loop supply chain. However, despite the significant number of publications addressing pricing issues for remanufactured products, little works has been done in the context of products with short life-cycle. Gan et al. (2015, 2017, 2018) are among those who addressed pricing decisions for short life-cycle products, aiming to keep both the new and remanufactured ones to stay competitively in the market. However, none of these incorporated the green consumer segments.

This paper presents models for pricing decision of new and remanufactured short-life-cycle products where green consumer segment exists and demand is sensitive to price. Two scenarios are compared. The first one is where the decision is taken independently between the retailer and the manufacturer. The second scenario is where the two parties jointly making decision on the prices. In the followings sections we present respectively the literature review, problem descriptions, optimization models, numerical example, and conclusions.

Literature review

Our study relates to two streams of the literature i.e. pricing of new and remanufactured products, and green consumers. In the first stream, the importance of pricing decision for new and remanufactured product in a closed-loop supply chain has been discussed in Guide and Wassenhove (2009), Atasu et al. (2010), and Souza (2013). They show that firms should manage the pricing strategy to avoid cannibalization, expand the market, and ensure profitability when engaging in remanufacturing practices. There are several works about pricing decision problem involving manufacturer or remanufacturer. Ferrer and Swaminathan (2006) study a problem where new and remanufactured products are not differentiated and sold in the same market with the same price. In the first period, manufacturer offers new product and in the next periods offers new and remanufactured product based on the returns from the first period. They develop models for finding optimum price and quantity that maximize profit with various planning horizons under monopoly and duopoly. Further, they extend the work by differentiating the price of new product from remanufactured one (Ferrer and Swaminathan 2010). Another pricing model is proposed by Ovchinnikov (2011) where new and remanufactured products are sold in the same market. They observe customer switching behavior and identify the proportion of customers who switch from purchasing new product to remanufactured product. In addition to new and remanufactured products' prices and quantities, Shi et al. (2011) also considered the cores acquisition price and find their optimum values that maximize the supply chain total profit. For short life-cycle product, Gan et al. (2015) propose a pricing and quantity decision model that involves a manufacturer, a retailer and a collector, for profit maximization. They consider two scenarios i.e. independently optimized profit under Stackelberg game with manufacturer as the leader, and joint profit optimization. The objective of the proposed model is to find the optimal wholesale and retail prices for both new and remanufactured products; and the optimal acquisition and transfer prices. Deng and Yang (2016) study the effect of the uncertain market size in the second period on the pricing strategies in the remanufacturing market. It is considered important because they find from empirical and experimental results that in reality market size is uncertain due to several factors such as environmental awareness, customer's psychological factors, and governments' policies. Furthermore, an insight into game-playing relationship between manufacturers and remanufacturers is provided, as well as optimum pricing strategy and its sensitivity analyses. Pricing and warranty level decisions problem for short life-cycle product is studied by Gan and Pujawan (2017) where manufacturer decides the optimum wholesale prices and warranty level that would maximize profit, while retailer decides the optimum retail prices. They find that optimum warranty level can be achieved regardless the initial warranty level set at the beginning of retailer's optimization, and remanufactured product's wholesale and retail prices are influenced by the expansion effectiveness coefficient. As for the sales channel, Gan et al. (2017) propose a pricing decision model for a closed-loop supply chain involving manufacturer, retailer, and collector, where the remanufactured products are sold via separate sales channel. Zhou et al. (2017) investigate pricing decision for remanufactured short life cycle technology where multiple generation product line is considered as it might result in cannibalization among various generation product line as well as new and remanufactured products. They consider two scenarios i.e. independent profit optimization and joint profit optimization. Zhou and Gupta (2019) extend the previous work, by extracting pricing data of new and remanufactured products for various generations from eBay. They propose price trend functions for these products with average quality, and also the technology depreciation rates.

Several studies are considering closed-loop supply chain with several players, namely manufacturer, retailer, collector, and remanufacturer. Qiaolun et al. (2008) propose pricing decision model using Stackelberg game with manufacturer as the leader, while retailer and collector are followers. They find optimum retail price, wholesale price, and collection price that would maximize profits. In this setting, new and remanufactured product are not differentiated, and considered as the same product with the same price. An empirical study that investigates consumer perceptions of remanufactured product is conducted by Abbey et al. (2015). They study consumers' responds to various discounts and brand equity manipulation of remanufactured product. The results show that discounting had a consistently positive, linear effect on remanufactured product attractiveness. However, brand equity manipulation turns out to be less important to consumers than specific remanufactured product quality perceptions. Another finding is that there exist green consumers who find remanufactured product is more interesting than new product. But, on the other hand, there also exist consumers who have negative attribute perceptions towards remanufactured product that significantly reduce its attractiveness. Gao et al. (2016) explore the effect of different channel power structures on the optimal retail price, investment in collection efforts, and sales efforts under centralized model. For the decentralized model, they use a game theory with three scenarios i.e. manufacturer Stackelber, vertical Nash, and retailer Stackelberg. It is shown that, when there is a dominant power shifting from the manufacturer to the retailer, manufacturer still can benefit from larger demand if collection effort is large enough. In addition, the performance of decentralized strategy can be improved with low price strategy. Jena and Sarmah (2014) study two remanufacturing firms that compete on price and service with random demand and uncertainty in collected used products. They develop a model for four remanufacturing configurations and find the equilibrium decisions, and identify the conditions under which manufacturers are able to use direct system or integrated system compared to global system. The results show that, when there is an increase in demand variation, direct system would be better. A return contract mechanism with quantity discount is proposed to coordinate the decentralized system. Wang and Hazen (2016) study pricing and production strategies in a capacitated hybrid manufacturing-remanufacturing system. A bidding mechanism is introduced for collecting returns, called name-your-own-price (NYOP) mechanism. Under this mechanism, manufacturer's optimal strategies depend on bidding cost, cost saving of remanufacturing, production capacity, and market scale. Manufacturer may perform pure manufacturing strategy when remanufacturing capacity becomes higher than manufacturing's. When compared to traditional list-price mechanism, NYOP mechanism is preferable to manufacturer under the conditions of low reverse market share, high manufacturing cost, sufficient capacity, or low capacity requirement of remanufacturing. Giri et al. (2017) study dual channel closed-loop supply chain, where the forward channel of new product is conducted through traditional retail channel and internet channel (e-tail), and the reverse channel is handled through traditional third party logistics and e-tail channel. There are five scenarios considered i.e. centralized, decentralized Nash, manufacturer-led, retailer-led, and third party-led decentralized scenarios.

They find that retailer-led decentralized scenario is the most profitable.

The second stream of the literature is exploring the existence of green consumers and their purchase behavior, and then discuss literature in pricing for remanufactured product with green consumers. Mostafa (2007) investigates the influence of cultural values and psychological factors on the green purchase behavior of Egyptian consumers. The results from the structural equation model show that consumers' natural environment orientation, ecological knowledge, and environmental concern influence their attitudes towards green purchase. However, the link between intention to purchase and actual purchase is low. Finisterra do Paço and Raposo (2010) conducted an empirical study on green consumer market segmentation in Portugal and find that there exist consumers with environmentally friendly behavior. They also identify environmental and demographic variables that can differentiate greener segment from other segments. It is also observed that green consumers possess certain attitudes and behaviors to minimize harmful impact on the environment. Michaud and Llerena (2011) study consumer willingness to purchase remanufactured product when they are informed the green aspect of it. An experimental auction was conducted and it is found that providing environmental information will increase consumers' willingness to pay for remanufactured product, and decrease consumers' willingness to pay for conventional product which is perceived to be more polluting product. However, there is no evidence that consumers are willing to pay premium for green product. Jiménez-Parra et al. (2014) conduct an empirical analysis to study the purchase intentions of potential consumers of remanufactured product and determine their basics characteristics. The findings confirm that key drivers for purchasing remanufactured products are respect for environment, price and brand reputation, and support from social environment. Wang and Hazen (2016) study how knowledge of remanufactured products in terms of cost, quality, and green attributes affects consumers' perception, and further affects consumers' purchase intentions in China. They find that perceived value has positive effect towards purchase intention. There are several factors that influence perceived value, which are quality knowledge, cost knowledge and green knowledge. Further study by Wang et al. (2018) reveals that there is a positive relation between consumers' greenness and their preference for remanufactured products. In addition, the relations between consumers' preferences for remanufactured products and price discount levels and product's green attributes are verified for three type of products i.e. technology, household and personal products. Vafadarnikjoo et al. (2018) study key factors for purchasing remanufactured bike using consumers' and experts' opinions. The results show that quality is the most significant motivation to purchase remanufactured product. The others factors are warranty, price, information provision, remanufacturer's reputation, value-added services and retailer's reputation. The abovementioned studies show that remanufactured product is viewed as a green product, and firms should take into account the existence of green consumers because the greenness of the product increases their purchase intention and willingness to pay.

Pricing strategy for remanufactured product with the existence of a green segment has been studied recently. Gu et al. (2015) study the effect of producing remanufacturable and non-remanufacturable new products to the production cost and consumer valuations. In addition, they investigate the environmental consequences of designing for remanufacturability, with the assumption that remanufacturable new products are valued higher, but remanufactured product are valued less than non-remanufacturable new product. Chen (2018) consider a supply chain where retailer is responsible for recycling, and manufacturer is responsible for remanufacturing. They apply game theoretic models for two scenarios, i.e., independently optimized based on Stackelberg equilibrum and Nash equilibrium, and joint pricing scenario within a cooperative game model. Ho et al. (2018) explore the effect of eco-friendly image of remanufacturing to the product's sales. In addition, they study the impacts of green consumers' purchase behaviors to products' random demands as well as to products' prices, and develop a model to find the optimum prices that maximize profit. The results show that when the size of the green market is large enough, new and remanufactured products can be easily distinguished, therefore, manufacturer need to gradually increase the price gap between two products such that consumers can differentiate them easily. A study on pricing decision and coordination of green electronic product is studied by Zhu and Yu (2018). They use dynamic game model to find optimal pricing strategy and the double marginal effect is coordinated through revenue-sharing contract, as well as two toll contracts. The degree of consumer preferences towards green remanufactured product is also studied, and they find that when the preference increases the service differentiation among new, remanufactured, and refurbished products is reduced. However, when the consumer preference is lower, it significantly affects the remanufactured product's price. Giri et al. (2018) develop two models with one manufacturer and one retailer. The first model considers price sensitive demand and is dependent on warranty period, while the second model considers price sensitive demand that is dependent on greening level and warranty period. The models are solved under three scenarios i.e. centralized, decentralized, and revenue-sharing contract. They conclude that the second model gives better results. Although the prices are higher, the market demand increases due to higher greening level for lower warranty period. These studies show that it is important to consider green consumers in pricing decision.

Our works is closely related to Giri et al. (2018) in terms of green consumers but we are focusing on short life-cycle products where the demand has specific characteristics. We consider price sensitive demand with green consumers, and the decision variables are the retail and wholesale prices of new and remanufactured products, and the green level that maximize the profits.

Problem description

The product considered in this study is a short life-cycle product which bears obsolescence effect after a certain period such that the demand would increase significantly in the introduction and growth phases, but decline rapidly afterwards. We use time frames that represent the product's life cycle, either for new and remanufactured products as shown in Fig. 1 where demand capacities of new and remanufactured products depends on the function characteristics or patterns as well as the length of time frames. A short life-cycle product usually has short useful life, which is typically less than 2 years (Kamath and Roy 2007), therefore it is reasonable to use a single period, since the future demand is not guaranteed (Galbreth and Blackburn 2005). Market is price sensitive, and there exists green segment. We consider manufacturer and retailer in the pricing decision, and explore two scenarios, i.e., independent and integrated scenario.

Demand capacity for this product is adopted from Gan et al. (2015), where the governing functions for the demand patterns are

$$d_n(t) = \begin{cases} d_{n1}(t) = \frac{U}{1+ke^{-\lambda Ut}}; 0 \le t \le \mu \\ d_{n2}(t) = \frac{U}{\lambda U(t-\mu)+\delta}; \mu \le t \le t_3 \end{cases} \quad \text{where} \quad \begin{matrix} k = \frac{U}{d_0} - 1 \\ \delta = 1 + ke^{-\lambda U\mu} \end{matrix}$$

$$d_r(t) = \begin{cases} d_{r1}(t) = \frac{V}{1+he^{-\eta V(t-t_1)}}; t_1 \le t \le t_3 \\ d_{r2}(t) = \frac{V}{\eta V(t-t_3)+\varepsilon}; t_3 \le t \le T \end{cases} \quad \text{where} \quad \begin{matrix} h = \frac{V}{d_{r0}} - 1 \\ \varepsilon = 1 + he^{-\eta V(t_3-t_1)} \end{matrix}$$

where $d_n(t)$ and $d_r(t)$ are the demand patterns for the new and the remanufactured products. U is maximum possible demand for the new product, μ is the time of highest demand, λ is the speed of the change in demand. Parallel definitions are applicable for V, t_3, d_{r0}, and η, respectively, for the remanufactured products

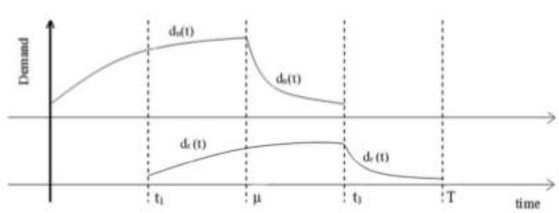

Fig. 1 Demand patterns for new and remanufactured products

Modeling assumptions

- Consumer can differentiate new and remanufactured product, therefore, the prices are differentiated. P_n is retail price of new product, and P_r is retail price of remanufactured product. Manufacturer also differentiates both products hence the wholesale prices are P_{nw} and P_{rw} for new and remanufactured products, respectively.
- Demand capacity depends on parameters of short life-cycle function characteristics, and we define D_n as demand capacity of new product and D_r as demand capacity of remanufactured product, as follows

$$D_n = \int_0^{\mu} \frac{U}{1+ke^{-\lambda Ut}} dt + \int_{\mu}^{t_3} \frac{U}{\lambda U(t-\mu)+\delta} dt$$
$$= \frac{1}{\lambda} \ln\left(\frac{\delta}{(1+k)e^{-\lambda U\mu}}\right) + \frac{1}{\lambda} \ln\left(\frac{\lambda U(t_3-\mu)+\delta}{\delta}\right)$$

$$D_r = \int_{t_1}^{t_3} \frac{V}{1+he^{-\eta V(t-t_1)}} dt + \int_{t_3}^{T} \frac{V}{\eta V(t-t_3)+\varepsilon} dt$$
$$= \frac{1}{\eta} \ln\left(\frac{\varepsilon}{(1+h)e^{-\eta V(t_3-t_1)}}\right) + \frac{1}{\eta} \ln\left(\frac{\eta V(T-t_3)+\varepsilon}{\varepsilon}\right)$$

- Green segment consumers value environmental-friendly product higher, therefore, they have higher preference towards remanufactured product, and might be willing to pay premium price for remanufactured product.
- The attractiveness of remanufactured product can be improved by manufacturer's efforts such as customer education, green campaign, green remanufacturing processes, and marketing. We define $\theta > 0$ as the green level, which means higher θ translates to higher attractiveness for green consumers.
- Demands are price sensitive and depend on market capacity. For remanufactured product, demand also increases linearly with green level (as in Gu et al. 2015; Giri et al. 2018; Zhu and Yu 2018). Therefore,

Demand of new product $= D_n(1 - aP_n + bP_r)$

Demand of remanufactured product $= D_r(1 - cP_r + eP_n + \gamma\theta)$

where $a, c > 0$ are demand's price sensitivity coefficient, $b, e > 0$ are substitute-product coefficient, and $\gamma > 0$ is green-level-demand-expansion coefficient

- The effort to implement a certain green level requires an investment and we use quadratic function to represent it (as in Gu et al. 2015, Giri et al. 2018), i.e. $\rho\theta^2$, where $\rho > 0$ is green-level-investment coefficient
- Unit cost of manufacturing new product is higher than unit cost of remanufacturing used product, i.e. $c_m > c_r$

Optimizations

Independent scenario

In this scenario, manufacturer and retailer are independently making pricing decision under Stackelberg game where manufacturer is the leader. The objective is to maximize profits. Demand information is known by manufacturer and retailer. At the beginning of the pricing mechanism, as the Stackelberg leader, manufacturer gather retailer's optimal response when given certain wholesale prices. Based on this response, manufacturer decides on new and remanufactured wholesale prices as well as the green level to maximize her profit. The backward induction process begins with retailer's optimization and is followed by manufacturer's optimization.

Retailer's optimization

$$\begin{aligned}\underset{P_n, P_r}{\text{Max}}\ \Pi_R = & D_n\left(1 - aP_n + bP_r\right)\left(P_n - P_{nw}\right) \\ & + D_r\left(1 - cP_r + eP_n + \gamma\theta\right)\left(P_r - P_{rw}\right)\end{aligned} \tag{1}$$

The respective first- and second-order derivatives are:

$$\begin{aligned}\frac{\partial \Pi_R}{\partial P_n} = & \left(-2aD_n\right)P_n + \left(bD_n + eD_r\right)P_r \\ & + \left(D_n\left(1 + aP_{nw}\right) - eP_{rw}D_r\right) = 0\end{aligned}$$

$$\begin{aligned}\frac{\partial \Pi_R}{\partial P_r} = & \left(bD_n + eD_r\right)P_n + \left(-2cD_r\right)P_r \\ & + \left(D_r\left(1 + cP_{rw} + \gamma\theta\right) - bP_{nw}D_n\right) = 0\end{aligned}$$

$$\frac{\partial^2 \Pi_R}{\partial P_n^2} = -2aD_n$$

$$\frac{\partial^2 \Pi_R}{\partial P_r^2} = -2cD_r$$

$$\frac{\partial^2 \Pi_R}{\partial P_n \partial P_r} = \frac{\partial^2 \Pi_R}{\partial P_r \partial P_n} = bD_n + eD_r$$

The Hessian matrix for this problem is

$$H_2 = \begin{bmatrix} -2aD_n & bD_n + eD_r \\ bD_n + eD_r & -2cD_r \end{bmatrix},$$

and $\left|H_2\right| = 4acD_nD_r - \left(bD_n + eD_r\right)^2$

It is obvious that the first sub-determinant is negative, i.e. $-2aD_n < 0$, and the second sub-determinant or the determinant of Hessian is positive when $4acD_nD_r > \left(bD_n + eD_r\right)^2$.

Proposition 1 The retailer's profit function Π_R is concave in P_n and P_r if

$$4acD_nD_r > \left(bD_n + eD_r\right)^2 \tag{2}$$

Proposition 2 The optimum retail price for new product (P_n^*) and optimum retail price for remanufactured product (P_r^*) in retailer's profit function are:

$$P_n^* = K_1P_{nw} + K_2P_{rw} + K_3\theta + K_4 \tag{3}$$

$$P_r^* = L_1P_{nw} + L_2P_{rw} + L_3\theta + L_4 \tag{4}$$

where

$$K_1 = \frac{(2ac - be)D_nD_r - b^2D_n^2}{4acD_nD_r - \left(bD_n + eD_r\right)^2} \quad L_1 = \frac{acD_nD_r - abD_n^2}{4acD_nD_r - \left(bD_n + eD_r\right)^2}$$

$$K_2 = \frac{bcD_nD_r - ceD_n^2}{4acD_nD_r - \left(bD_n + eD_r\right)^2} \quad L_2 = \frac{(2ac - be)D_nD_r - e^2D_r^2}{4acD_nD_r - \left(bD_n + eD_r\right)^2}$$

$$K_3 = \frac{\gamma\left(bD_nD_r + eD_r^2\right)}{4acD_nD_r - \left(bD_n + eD_r\right)^2} \quad L_3 = \frac{2a\gamma D_nD_r}{4acD_nD_r - \left(bD_n + eD_r\right)^2}$$

$$K_4 = \frac{(b + 2c)D_nD_r + eD_r^2}{4acD_nD_r - \left(bD_n + eD_r\right)^2} \quad L_4 = \frac{(2a + e)D_nD_r + bD_n^2}{4acD_nD_r - \left(bD_n + eD_r\right)^2}$$

Manufacturer's optimization

$$\begin{aligned}\underset{P_{nw}, P_{rw}, \theta}{\text{Max}}\ \Pi_M = & D_n\left(1 - aP_n + bP_r\right)\left(P_{nw} - c_m\right) \\ & + D_r\left(1 - cP_r + eP_n + \gamma\theta\right)\left(P_{rw} - c_r\right) - \rho\theta^2\end{aligned} \tag{5}$$

subject to retailer's responses to manufacturer's wholesale prices, which are P_n^* and P_r^* as given in Proposition 2.

Hence, manufacturer's optimization problem can be expressed as

$$\begin{aligned}\underset{P_{nw}, P_{rw}, \theta}{\text{Max}}\ \Pi_M = & D_n\left(1 - a\left(K_1P_{nw} + K_2P_{rw} + K_3\theta + K_4\right) + b\left(L_1P_{nw} + L_2P_{rw} + L_3\theta + L_4\right)\right)\left(P_{nw} - c_m\right) \\ & + D_r\left(1 - c\left(L_1P_{nw} + L_2P_{rw} + L_3\theta + L_4\right) + e\left(K_1P_{nw} + K_2P_{rw} + K_3\theta + K_4\right) + \gamma\theta\right)\left(P_{rw} - c_r\right) - \rho\theta^2\end{aligned} \tag{6}$$

The first- and second-order derivatives are:

$$\frac{\partial \Pi_M}{\partial P_{nw}} = \{2D_n(-aK_1 + bL_1)\}P_{nw} + \{(-aK_2 + bL_2)D_n + (-cL_1 + eK_1)D_r\}P_{rw} + \{D_n(-aK_3L_3\}\theta - \{D_n((-aK_1 + bL_1)c_m - (1 - aK_4 + bL_4)) + D_r(-cL_1 + eK_1)c_r\} = 0$$

$$\frac{\partial \Pi_M}{\partial P_{rw}} = \{(-aK_2 + bL_2)D_n + (-cL_1 + eK_1)D_r\}P_{nw} + \{2D_r(-cL_2 + eK_2)\}P_{rw} + \{D_r(-cL_3 + eK_3 + \gamma)\}\theta - \{D_n(-aK_2 + bL_2)c_m + D_r((-cL_2 + eK_2)c_r - (1 - cL_4 + eK_4)\} = 0.$$

$$\frac{\partial \Pi_M}{\partial \theta} = \{D_n(-aK_3 + bL_3)\}P_{nw} + \{D_r(-cL_3 + eK_3 + \gamma)\}P_{rw} + \{-2\rho\}\theta - \{D_n(-aK_3 + bL_3)c_m + D_r(-cL_3 + eK_3 + \gamma)c_r\} = 0$$

$$\frac{\partial^2 \Pi_M}{\partial P_{nw}^2} = 2D_n(-aK_1 + bL_1) = A_{11}$$

$$\frac{\partial^2 \Pi_M}{\partial P_{rw}^2} = 2D_r(-cL_2 + eK_2) = A_{22}$$

$$\frac{\partial^2 \Pi_M}{\partial \theta^2} = -2\rho = A_{33}$$

$$\frac{\partial^2 \Pi_M}{\partial P_{nw}\partial P_{rw}} = \frac{\partial^2 \Pi_M}{\partial P_{rw}\partial P_{nw}} = D_n(-aK_2 + bL_2) + D_r(-cL_1 + eK_1) = A_{12}$$

$$\frac{\partial^2 \Pi_M}{\partial P_{nw}\partial \theta} = \frac{\partial^2 \Pi_M}{\partial \theta \partial P_{nw}} = D_r(-aK_3 + bL_3) = A_{13}$$

$$\frac{\partial^2 \Pi_M}{\partial P_{rw}\partial \theta} = \frac{\partial^2 \Pi_M}{\partial \theta \partial P_{rw}} = D_r(-cL_3 + eK_3 + \gamma) = A_{23}$$

The Hessian matrix of manufacturer's optimization problem is

$$H_3 = \begin{bmatrix} A_{11} & A_{12} & A_{13} \\ A_{12} & A_{22} & A_{23} \\ A_{13} & A_{23} & A_{33} \end{bmatrix}$$

The first sub-determinant A_{11} is negative, the second sub-determinant i.e. $A_{11}A_{22} - A_{12}^2$ should be positive, and $|H_3|$ should be negative to ensure concavity.

Proposition 3 The manufacturer's profit function Π_M is concave in P_{nw}, P_{rw} and θ if

(a) $aK_1 - bL_1 > 0$ (7)

(b) $4D_nD_r(-aK_1 + bL_1)(-cL_2 + eK_2) - (D_n(-aK_2 + bL_2) + D_r(-cL_1 + eK_1))^2 > 0$ (8)

(c)

$$\begin{bmatrix} 2D_n(-aK_1 + bL_1) & D_n(-aK_2 + bL_2) + D_r(-cL_1 + eK_1) & D_r(-aK_3 + bL_3) \\ D_n(-aK_2 + bL_2) + D_r(-cL_1 + eK_1) & 2D_r(-cL_2 + eK_2) & D_r(-cL_3 + eK_3 + \gamma) \\ D_r(-aK_3 + bL_3) & D_r(-cL_3 + eK_3 + \gamma) & -2\rho \end{bmatrix} < 0 \quad (9)$$

Proposition 4 The optimum wholesale price for new product (P_{nw}^*), optimum wholesale price for remanufactured product (P_{rw}^*), and optimum green level (θ^*) for manufacturer's profit function are the solution to the following linear system:

$$\begin{bmatrix} 2D_n(-aK_1+bL_1) & D_n(-aK_2+bL_2)+D_r(-cL_1+eK_1) & D_r(-aK_3+bL_3) \\ D_n(-aK_2+bL_2)+D_r(-cL_1+eK_1) & 2D_r(-cL_2+eK_2) & D_r(-cL_3+eK_3+\gamma) \\ D_r(-aK_3+bL_3) & D_r(-cL_3+eK_3+\gamma) & -2\rho \end{bmatrix}\begin{bmatrix} P_{nw} \\ P_{rw} \\ \theta \end{bmatrix} = \begin{bmatrix} D_n((-aK_1+bL_1)c_m-(1-aK_4+bL_4))+D_r(-cL_1+eK_1)c_r \\ D_n(-aK_2+bL_2)c_m+D_r((-cL_2+eK_2)c_r-(1-cL_4-eK_4)) \\ D_n(-aK_3+bL_3)c_m+D_r(-cL_3+eK_3+\gamma)c_r \end{bmatrix} \tag{10}$$

Integrated decision

Under the integrated decision scenario, manufacturer and retailer are jointly making the pricing decisions as well as the green level with a goal to maximize total profit. In this setting, manufacturer and retailer make pricing decision as a unity so the only pricing decision considered are the retail prices which directly impact the demand. They sign a contract on revenue sharing where a certain portion (φ) of the revenue will be received by manufacturer and the rest of it by retailer, and the manufacturer agrees to offer lower wholesale prices. The integrated profit function is the summation of retailer's and manufacturer's profit functions, so the optimization problem becomes

$$\begin{aligned}\underset{P_n,P_r,\theta}{\text{Max}}\ \Pi_J =& \{D_n(1-aP_n+bP_r)(\varphi P_n+P_{nw}-c_m) \\ &+D_r(1-cP_r+eP_n+\gamma\theta)(\varphi P_r+P_{rw}-c_r)-\rho\theta^2\} \\ &+\{D_n(1-aP_n+bP_r)((1-\varphi)P_n-P_{nw}) \\ &+D_r(1-cP_r+eP_n+\gamma\theta)((1-\varphi)P_r-P_{rw})\}\end{aligned} \tag{11}$$

$$\begin{aligned}\underset{P_n,P_r,\theta}{\text{Max}}\ \Pi_J =& D_n(1-aP_n+bP_r)(P_n-c_m) \\ &+D_r(1-cP_r+eP_n+\gamma\theta)(P_r-c_r)-\rho\theta^2\end{aligned} \tag{12}$$

The first and second derivatives are:

$$\frac{\partial \Pi_J}{\partial P_n} = (-2aD_n)P_n + (bD_n+eD_r)P_r + (D_n(1+ac_m)-ec_rD_r) = 0$$

$$\begin{aligned}\frac{\partial \Pi_J}{\partial P_r} =& (bD_n+eD_r)P_n + (-2cD_r)P_r + (\gamma D_r)\theta \\ &+ (D_r(1+cc_r)-bc_mD_r) = 0.\end{aligned}$$

$$\frac{\partial \Pi_J}{\partial \theta} = (\gamma D_r)P_r + (-2\rho)\theta + (-\gamma D_r c_r) = 0.$$

$$\frac{\partial^2 \Pi_J}{\partial P_n^2} = -2aD_n$$

$$\frac{\partial^2 \Pi_J}{\partial P_r^2} = -2cD_r$$

$$\frac{\partial^2 \Pi_J}{\partial \theta^2} = -2\rho$$

$$\frac{\partial^2 \Pi_J}{\partial P_n \partial P_r} = \frac{\partial^2 \Pi_J}{\partial P_r \partial P_n} = bD_n + eD_r$$

$$\frac{\partial^2 \Pi_J}{\partial P_n \partial \theta} = \frac{\partial^2 \Pi_J}{\partial \theta \partial P_n} = 0$$

$$\frac{\partial^2 \Pi_J}{\partial P_r \partial \theta} = \frac{\partial^2 \Pi_J}{\partial \theta \partial P_r} = \gamma D_r$$

The concavity of this problem can be inspected from the Hessian matrix,

$$H_3 = \begin{bmatrix} -2aD_n & bD_n+eD_r & 0 \\ bD_n+eD_r & -2cD_r & \gamma D_r \\ 0 & \gamma D_r & -2\rho \end{bmatrix}$$

$$|H_3| = -2\rho\left(4acD_nD_r - (bD_n+eD_r)^2\right) + 2a\gamma^2 D_n D_r^2$$

The first sub-determinant $-2aD_n$ is obviously negative. The second sub-determinant i.e. $4acD_nD_r - (bD_n+eD_r)^2$ should be positive, and $|H_3|$ should be negative to ensure concavity.

Proposition 5 The joint profit function Π_J is concave in P_n, P_r and θ if

(a) $4acD_nD_r > (bD_n+eD_r)^2$ (13)

(b) $\rho\left(4acD_nD_r - (bD_n+eD_r)^2\right) - a\gamma^2 D_n D_r^2 > 0$ (14)

Proposition 6 The optimal selling price for new product (P_n^*) and remanufactured product (P_r^*), and the green level (θ^*) in the joint model scenario are:

$$P_n^* = \frac{\left(4c\rho D_r - \gamma^2 D_r^2\right)G_1 + \left(\gamma^2 D_r^2 c_r + 2\rho G_2\right)\left(bD_n + eD_r\right)}{-2\rho\left(4acD_nD_r - \left(bD_n + eD_r\right)^2\right) + 2a\gamma^2 D_n D_r^2} \quad (15)$$

$$P_r^* = \frac{4a\rho D_n G_2 + 2\rho G_1\left(bD_n + eD_r\right) + 2ac_r\gamma^2 D_n D_r^2}{-2\rho\left(4acD_nD_r - \left(bD_n + eD_r\right)^2\right) + 2a\gamma^2 D_n D_r^2} \quad (16)$$

$$\theta^* = \frac{4ac\gamma c_r D_n D_r^2 + \gamma D_r G_1\left(bD_n + eD_r\right) - \gamma D_r c_r\left(bD_n + eD_r\right)^2 + 2a\gamma D_n D_r G_2}{-2\rho\left(4acD_nD_r - \left(bD_n + eD_r\right)^2\right) + 2a\gamma^2 D_n D_r^2} \quad (17)$$

where

$$G_1 = -\left(1 + ac_m\right)D_n + ec_r D_r$$

$$G_2 = bc_m D_n - \left(1 + cc_r\right)D_r$$

Proposition 7 Under the optimum setting in the integrated decision problem, relations between green level and (1) demand capacity for remanufactured product, (2) selling price of remanufactured product, (3) remanufacturing cost are as follow

(1) $\frac{\partial\theta}{\partial D_r} > 0$, which shows that the green level increases when the demand capacity for remanufactured product increases. With higher demand potential for remanufactured product, manufacturer gets higher opportunity to attract the green segment by increasing the green level;

(2) $\frac{\partial\theta}{\partial P_r} > 0$, this result shows that the green level increases as the price of remanufactured product increases. Since the market is price sensitive, as the price is getting higher, manufacturer needs to offer a higher green level of the remanufactured product to the green segment, as to maintain the sales level;

(3) $\frac{\partial\theta}{\partial c_r} < 0$, explains the decrease in green level as the remanufacturing cost increases. The higher the remanufacturing cost, manufacturer would decrease the green level to maintain selling price as well as profit margin.

Proof: See "Appendix 1" section.

Revenue sharing between manufacturer and retailer depends on φ, the contracted revenue sharing portion, hence

- Manufacturer's profit per unit of new product $= \varphi P_n + P_{nw} - c_m$
- Manufacturer's profit per unit of remanufactured product $= \varphi P_r + P_{rw} - c_r$
- Retailer's profit per unit of new product $= (1-\varphi)P_n - P_{nw}$
- Retailer's profit per unit of remanufactured product $= (1-\varphi)P_r - P_{rw}$

Numerical example

In this numerical example we use price sensitivity parameters that are similar to (Gan et al. 2018) i.e. $a = 0.003, b = 0.0001, c = 0.004$, and $e = 0.0002$. The parameters describing demand capacity of short life-cycle products, or in brief we use the term 'short life-cycle determinants' are similar to Gan et al. (2015), where new product's parameters are $U = 1000$, $D_0 = 90$, with varying $\lambda = 0.05$, and remanufactured product's are $V = 500$, $D_{r0} = 50$, and $\eta = 0.05$. Selling horizon consists of four time segments with $t_1 = 1, \mu = 2, t_3 = 3$, and $T = 4$. The unit manufacturing and remanufacturing costs are $c_m = 90$ and $c_r = 60$ respectively. Parameters related to the green level are $\gamma = 0.002$, and $\rho = 20$. The optimization problems are solved using Matlab R2014, and the results are analyzed to find the behavior of pricing decision when green consumers are considered. In addition, sensitivity analyses are conducted by varying several important parameters, namely, the green-level-demand-expansion coefficient, the unit remanufacturing cost, the demand parameters, and the short life-cycle determinants, to see their effects to the profit of manufacturer, retailer and the total profit.

Numerical example results for independent decision problem

The results of independent decision problem is shown in Table 1. The green level responses to the model parameters can be observed in Figs. 2 and 3. The increment in demand parameter that represents new product's price sensitivity (a) is responded by higher optimum green level. As the market is getting more sensitive to new product's price, the attractiveness of remanufactured product can be improved by increasing green level, especially for green consumers. When green-level-demand-expansion coefficient (γ) increases, the optimum green level also increases, because the effectiveness of increasing it is higher. However,

Table 1 Numerical example's results varying $\lambda, \eta, \gamma, c_r, a, c, \rho$ (independent decision)

lmbd	nu	a	b	cr	gamma	rho	Pnw	Pn	Qnty_n	Prw	Pr	Qnty-r	theta	Profit_M	Profit_R	Total Profit
0.01	***0.01***	0.003	0.004	60	0.002	20	211.71	273.69	406.39	118.64	243.66	78.57	1.36	54,029.94	35,012.28	89,042.21
0.05	***0.05***	0.003	0.004	60	0.002	20	210.92	273.66	412.89	118.11	243.14	86.65	1.43	54,921.19	36,737.25	91,658.44
0.1	***0.1***	0.003	0.004	60	0.002	20	210.90	273.66	411.18	118.09	243.12	86.47	1.42	54,694.96	36,614.47	91,309.44
0.2	***0.2***	0.003	0.004	60	0.002	20	210.91	273.66	409.63	118.10	243.13	86.03	1.42	54,488.51	36,457.59	90,946.10
0.05	0.05	0.003	0.004	60	***0.0005***	20	210.99	273.70	412.51	117.43	242.48	86.61	0.35	54,881.14	36,698.26	91,579.40
0.05	0.05	0.003	0.004	60	***0.001***	20	210.98	273.69	412.58	117.56	242.61	86.62	0.70	54,889.14	36,705.90	91,595.05
0.05	0.05	0.003	0.004	60	***0.002***	20	210.92	273.66	412.89	118.11	243.14	86.65	1.43	54,921.19	36,737.25	91,658.44
0.05	0.05	0.003	0.004	60	***0.005***	20	210.46	273.39	415.43	122.63	247.53	86.91	4.14	55,140.80	36,997.72	92,138.51
0.05	0.05	0.003	0.004	60	***0.01***	20	205.90	270.74	440.31	167.02	290.58	89.47	19.60	52,927.42	39,601.19	92,528.61
0.05	0.05	0.003	0.004	***40***	0.002	20	208.96	272.92	416.43	108.93	238.35	108.18	2.49	56,873.39	40,631.61	97,505.00
0.05	0.05	0.003	0.004	***50***	0.002	20	209.94	273.29	414.66	113.52	240.75	97.42	1.96	55,846.41	38,659.73	94,506.14
0.05	0.05	0.003	0.004	***60***	0.002	20	210.92	273.66	412.89	118.11	243.14	86.65	1.43	54,921.19	36,737.25	91,658.44
0.05	0.05	0.003	0.004	***70***	0.002	20	211.90	274.03	411.12	122.70	245.53	75.89	0.90	54,097.74	34,864.16	88,961.90
0.05	0.05	***0.002***	0.004	60	0.002	20	298.01	402.01	450.98	104.52	261.23	37.63	0.73	95,472.76	52,800.05	148,272.82
0.05	0.05	***0.003***	0.004	60	0.002	20	210.92	273.66	412.89	118.11	243.14	86.65	1.43	54,921.19	36,737.25	91,658.44
0.05	0.05	***0.004***	0.004	60	0.002	20	168.43	210.19	370.90	124.74	234.28	110.54	1.77	36,185.62	27,595.26	63,780.88
0.05	0.05	***0.005***	0.004	60	0.002	20	143.27	172.33	327.41	128.67	229.02	124.68	1.97	25,925.63	22,025.33	47,950.95
0.05	0.05	0.003	***0.002***	60	0.002	20	213.14	275.69	443.10	265.64	452.96	170.28	8.94	87,979.40	59,615.87	147,595.27
0.05	0.05	0.003	***0.003***	60	0.002	20	210.43	273.72	426.46	166.60	311.98	129.02	3.90	64,809.51	45,747.01	110,556.52
0.05	0.05	0.003	***0.004***	60	0.002	20	210.92	273.66	412.89	118.11	243.14	86.65	1.43	54,921.19	36,737.25	91,658.44
0.05	0.05	0.003	***0.005***	60	0.002	20	211.69	273.94	406.55	102.01	220.47	65.09	0.61	52,201.68	33,017.78	85,219.46
0.05	0.05	0.003	0.004	60	0.002	***10***	210.84	273.61	413.32	118.87	243.88	86.70	2.93	54,963.95	36,781.06	91,745.01
0.05	0.05	0.003	0.004	60	0.002	***20***	210.92	273.66	412.89	118.11	243.14	86.65	1.43	54,921.19	36,737.25	91,658.44
0.05	0.05	0.003	0.004	60	0.002	***30***	210.95	273.67	412.75	117.86	242.90	86.64	0.94	54,906.94	36,723.16	91,630.10
0.05	0.05	0.003	0.004	60	0.002	***40***	210.96	273.68	412.68	117.74	242.78	86.63	0.70	54,899.82	36,716.21	91,616.03

The bold numbers are the parameter values that are varied for sensitivity analysis

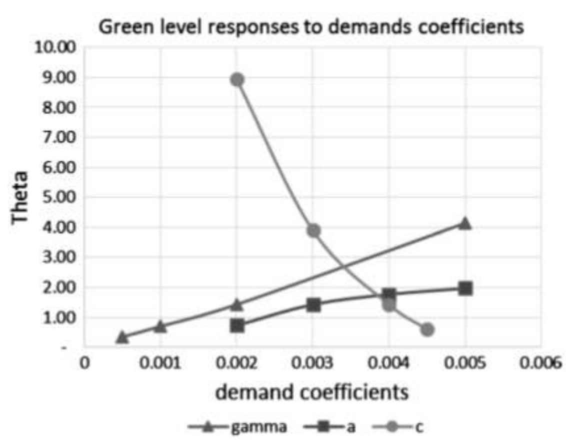

Fig. 2 The effect of price sensitivity (a, c) and green-level-demand-expansion coefficient (γ) (independent scenario)

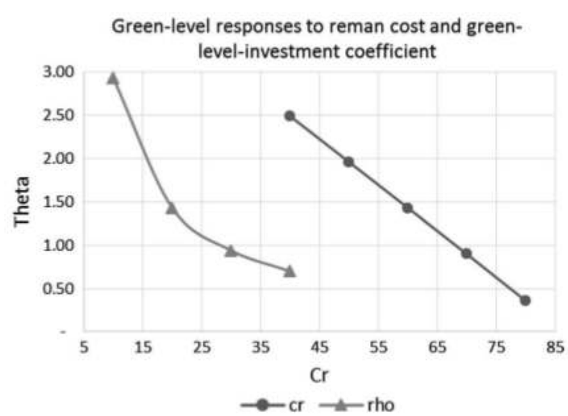

Fig. 3 The effect of remanufacturing cost (c_r) and green-level-investment coefficient (ρ) (independent scenario)

when remanufactured product's price sensitivity to remanufactured product's demand increases, it is followed by a decreasing green level, since the market is more sensitive to remanufactured product's price, so the effort to improve green level would not be effective. Figure 3 shows the effect of remanufacturing cost to green level which is inversely proportional. The higher the remanufacturing cost the lower

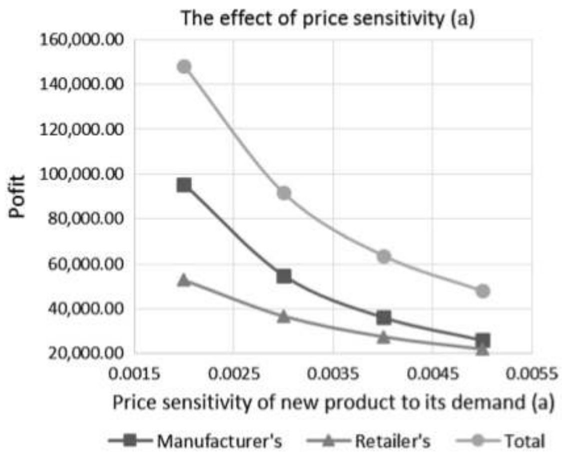

Fig. 4 The effect of price sensitivity (a) to manufacturer's, retailer's and total profits (independent scenario)

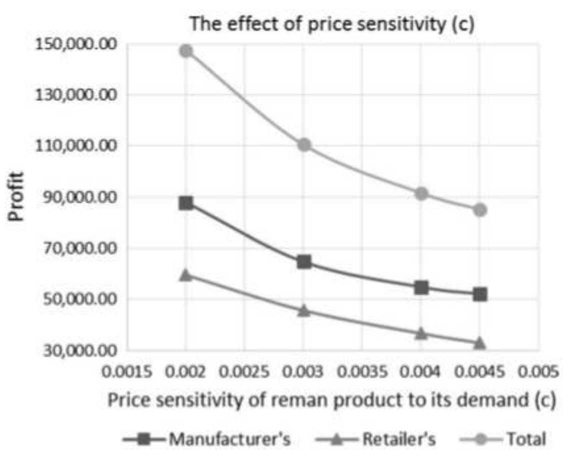

Fig. 5 The effect of price sensitivity (c) to manufacturer's, retailer's and total profits (independent scenario)

is the optimum green level, which is described in proposition 7. In addition, as the green-level-investment coefficient (ρ) increases the optimum green level decreases.

The sensitivity analysis plots are shown in Figs. 4, 5, 6, 7, 8, and 9 as follows

- The higher customers' price sensitivity to new products (a), the lower the profits of both manufacturer and retailer, as seen in Fig. 4. However, manufacturer's profit plummets faster than retailer's. On the other hand, an increase in customer's price sensitivity to remanufactured product (c) would decrease the profits, but now retailer's profit declines more rapidly. Figure 5 shows this result. The existence of green segment allows remanufactured product's retail price to be higher than new product's. When c is lower, the demand capacity of remanufactured product is absorbed better and it is also responded by higher optimum green level to attract green consumers, as shown in Table 1, therefore, the optimum retail price is higher. This results shows that firm should perform market survey to determine price sensitivity and then use them to decide green segment strategies for pricing decisions.
- The effect of demand's speed of change represented by λ for new product, and η for remanufactured product can be observed in Fig. 6, where the highest profit is

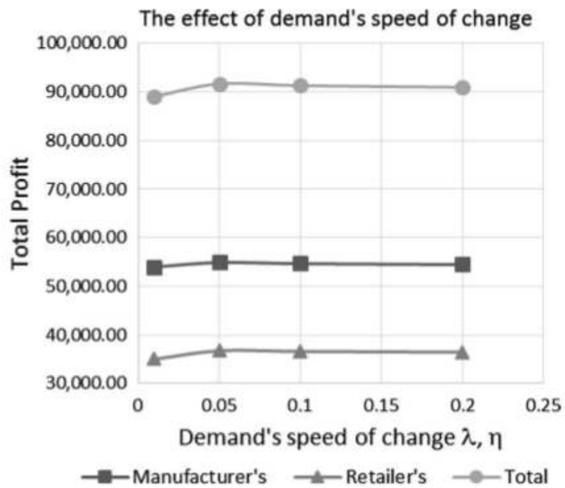

Fig. 6 The effect of demand's speed of change (λ, η) to manufacturer's, retailer's and total profits (independent scenario)

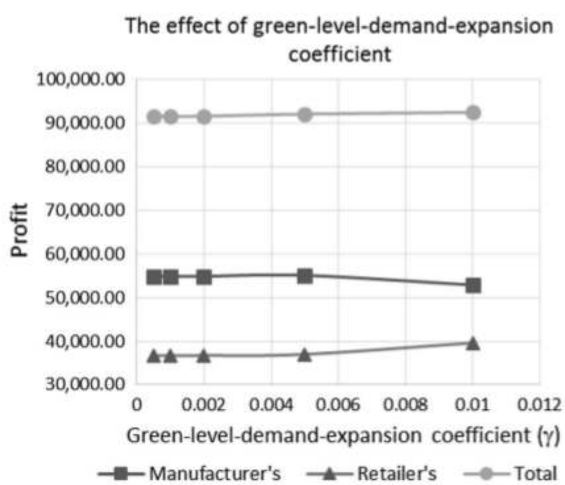

Fig. 7 The effect of green-level-demand-expansion coefficient (γ) to manufacturer's, retailer's, and total profits (independent scenario)

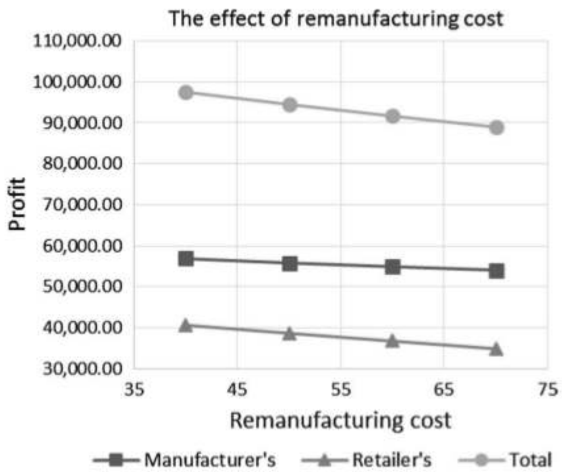

Fig. 8 The effect of remanufacturing cost (c_r) to manufacturer's, retailer's and total profits (independent scenario)

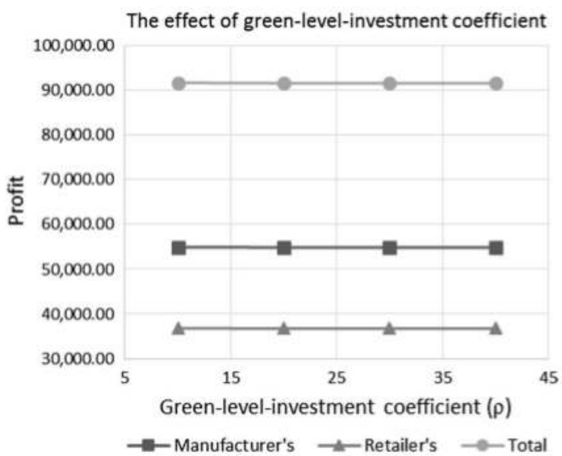

Fig. 9 The effect of green-level-investment coefficient to manufacturer's, retailer's and total profits (independent scenario)

attained at 0.05 either for manufacturer or retailer. This result shows that it is important that firm manages the promotion such that the increase in demand would not be too fast to achieve sufficient demand capacity during the growth period before it decreases fast due to short life-cycle characteristic.

- Manufacturer's profit is increasing with green-level-demand-expansion coefficient (γ) until $\gamma = 0.005$ but decreasing at $\gamma = 0.01$, but for retailer it is always increasing, as shown in Fig. 7. When γ is getting higher, it is responded by a very high optimum green level, therefore, the attractiveness of remanufactured product is increasing significantly followed by higher remanufactured product's prices and lower new product's prices, which is then reduce manufacturer's profit, which can be observed in Table 1. When green segment is quite large, then γ is quite high, and firms should increase the green level of the product to attract green consumers, but not too high as it would erode the sales of the new product.
- Remanufacturing cost (c_r) is inversely proportional to profits received by manufacturer as well as retailer, which is shown in Fig. 8. This can be explained by the effect of remanufacturing cost to retail prices. When c_r is higher, prices are increasing, which then decrease the demanded products. In addition, the optimum green level is decreasing because otherwise it would be too costly for remanufactured product.
- Green-level-investment coefficient (ρ) does not have significant effect to profit earned as shown in Fig. 9, because the higher ρ is responded by lower optimum green level, and it keeps the prices relatively stable, as seen in Table 1.

Numerical example results for integrated decision problem

In this setting, manufacturer and retailer act as one unit and make pricing decision that maximize total profit. The wholesale prices are agreed to be $P_{nw} = 90$ and $P_{rw} = 40$, and contracted revenue sharing portion is $\varphi = 40\%$. The results can be seen in Table 2.

Total profit in integrated decision is 32.5% higher than independent scenario. Since the contract requires the manufacturer to provide lower wholesale price, then retail prices also become lower. Retail price for new product in integrated scenario is 26.6% lower than independent scenario, and retail price for remanufactured product is 47.5% lower. Demand for new product increases 44.7% and for remanufactured product 73.2%. The revenue sharing contract also enable both manufacturer and retailer to receive higher profit i.e. 33.4% and 31.1%, respectively, compared to independent scenario.

The sensitivity of parameters are consistent with the independent scenario as shown in Figs. 10, 11, 12, 13, 14, and 15. It is observed when green-level-demand-expansion coefficient increases to $\gamma = 0.01$, retailer's profit exceeds manufacturer's profit, because the optimum green level is increasing significantly which required higher investment by manufacturer. On the other hand, the price of remanufactured product is increasing as a respond to higher interest of green consumers to buy remanufactured product, which is beneficial to the retailer. In addition, the effect of remanufacturing cost in the integrated scenario is less significant since the wholesale prices are contracted as fixed values.

Table 2 Numerical example's results varying $\lambda, \eta, \gamma, c_r, a, c, \rho$ (integrated decision)

lmbd	nu	a	b	cr	gamma	rho	Pnw	Pn	Qnty_n	Prw	Pr	Qnty-r	theta	Profit_M	Profit_R	Total Profit
0.01	***0.01***	0.003	0.004	60	0.002	20	90.00	216.08	736.16	40.00	164.97	373.22	4.98	80,294.10	51,198.56	131,492.67
0.05	***0.05***	0.003	0.004	60	0.002	20	90.00	216.17	747.18	40.00	164.88	401.93	5.34	82,505.19	53,349.59	135,854.78
0.1	***0.1***	0.003	0.004	60	0.002	20	90.00	216.17	744.07	40.00	164.87	400.82	5.33	82,188.09	53,159.88	135,347.96
0.2	***0.2***	0.003	0.004	60	0.002	20	90.00	216.17	741.28	40.00	164.87	398.92	5.30	81,864.11	52,935.62	134,799.73
0.05	0.05	0.003	0.004	60	***0.0005***	20	90.00	216.13	747.18	40.00	163.63	396.82	1.32	82,594.95	52,730.71	135,325.66
0.05	0.05	0.003	0.004	60	***0.001***	20	90.00	216.14	747.18	40.00	163.88	397.83	2.65	82,577.78	52,852.68	135,430.47
0.05	0.05	0.003	0.004	60	***0.002***	20	90.00	216.17	747.18	40.00	164.88	401.93	5.34	82,505.19	53,349.59	135,854.78
0.05	0.05	0.003	0.004	60	***0.005***	20	90.00	216.42	747.17	40.00	172.52	433.00	14.33	81,793.66	57,278.45	139,072.11
0.05	0.05	0.003	0.004	60	***0.01***	20	90.00	217.74	747.16	40.00	212.05	593.88	38.74	73,557.07	82,172.76	155,729.83
0.05	0.05	0.003	0.004	***40***	0.002	20	90.00	216.17	745.14	40.00	155.01	443.22	5.86	91,226.95	53,079.33	144,306.27
0.05	0.05	0.003	0.004	***50***	0.002	20	90.00	216.17	746.16	40.00	159.95	422.57	5.60	86,701.71	53,275.60	139,977.30
0.05	0.05	0.003	0.004	***60***	0.002	20	90.00	216.17	747.18	40.00	164.88	401.93	5.34	82,505.19	53,349.59	135,854.78
0.05	0.05	0.003	0.004	***70***	0.002	20	90.00	216.17	748.19	40.00	169.82	381.28	5.09	78,637.40	53,301.32	131,938.72
0.05	0.05	***0.002***	0.004	60	0.002	20	90.00	301.97	838.54	40.00	169.22	402.19	5.57	119,846.67	101,208.27	221,054.93
0.05	0.05	***0.003***	0.004	60	0.002	20	90.00	216.17	747.18	40.00	164.88	401.93	5.34	82,505.19	53,349.59	135,854.78
0.05	0.05	***0.004***	0.004	60	0.002	20	90.00	173.32	655.80	40.00	162.72	401.80	5.23	63,034.30	32,332.88	95,367.18
0.05	0.05	***0.005***	0.004	60	0.002	20	90.00	147.63	564.43	40.00	161.42	401.72	5.17	50,700.98	22,036.41	72,737.39
0.05	0.05	0.003	***0.002***	60	0.002	20	90.00	220.81	747.12	40.00	303.77	470.29	12.42	110,639.84	98,644.56	209,284.40
0.05	0.05	0.003	***0.003***	60	0.002	20	90.00	217.70	747.16	40.00	210.72	434.88	7.68	91,841.35	67,938.59	159,779.93
0.05	0.05	0.003	***0.004***	60	0.002	20	90.00	216.17	747.18	40.00	164.88	401.93	5.34	82,505.19	53,349.59	135,854.78
0.05	0.05	0.003	***0.005***	60	0.002	20	90.00	215.66	747.18	40.00	149.70	385.85	4.57	79,425.75	48,660.55	128,086.31
0.05	0.05	0.003	0.004	60	0.002	***10***	90.00	216.22	747.17	40.00	166.26	407.52	10.83	82,398.20	54,035.30	136,433.50
0.05	0.05	0.003	0.004	60	0.002	***20***	90.00	216.17	747.18	40.00	164.88	401.93	5.34	82,505.19	53,349.59	135,854.78
0.05	0.05	0.003	0.004	60	0.002	***30***	90.00	216.15	747.18	40.00	164.43	400.10	3.55	82,538.24	53,126.95	135,665.19
0.05	0.05	0.003	0.004	60	0.002	***40***	90.00	216.15	747.18	40.00	164.21	399.19	2.66	82,554.29	53,016.71	135,571.00

The bold numbers are the parameter values that are varied for sensitivity analysis

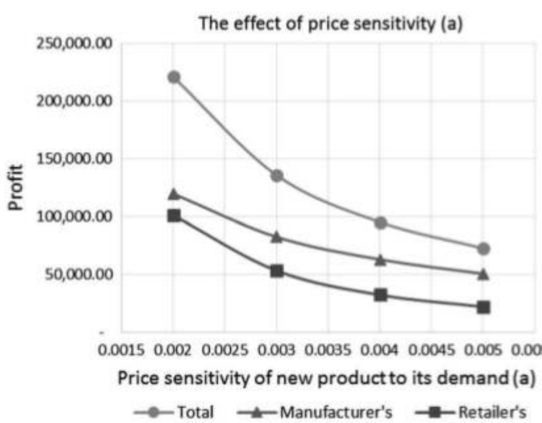

Fig. 10 The effect of price sensitivity (a) to manufacturer's, retailer's and total profits (integrated scenario)

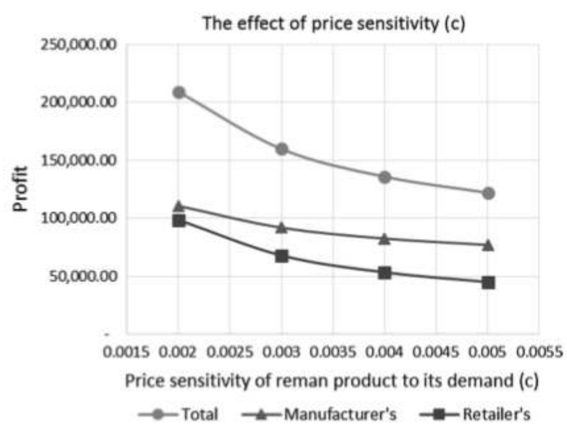

Fig. 11 The effect of price sensitivity (c) to manufacturer's, retailer's and total profits (integrated scenario)

Managerial implications

From the optimum results and the numerical example with sensitivity analyses, we provide several managerial implications as follows:

- The existence of green segment is beneficial to manufacturer as well as retailer, as it increases their profits. Therefore, managers need to perform sound market survey to identify the green segment and their willing-

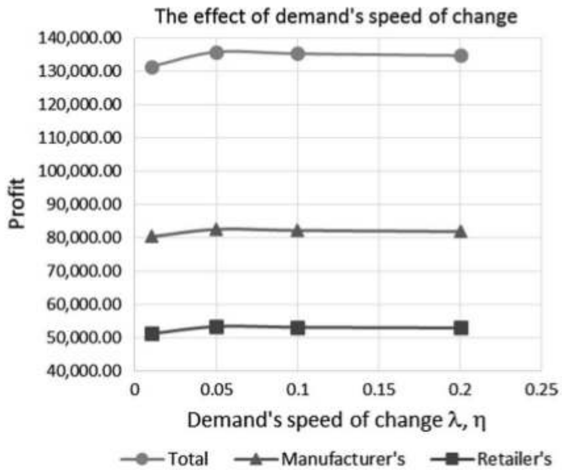

Fig. 12 The effect of demand's speed of change (λ, η) to manufacturer's, retailer's, and total profits (integrated scenario)

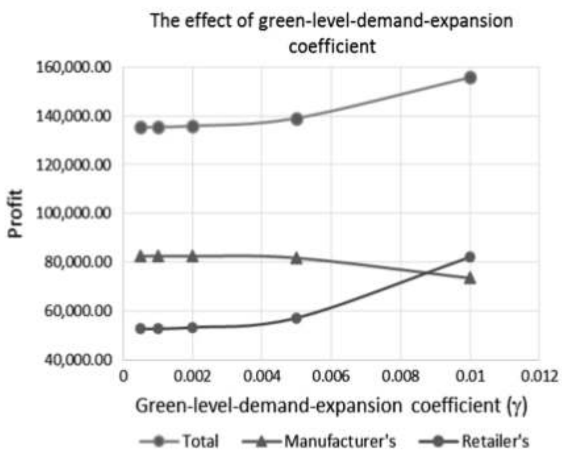

Fig. 13 The effect of green-level-demand-expansion coefficient (γ) to manufacturer's, retailer's, and total profits (integrated scenario)

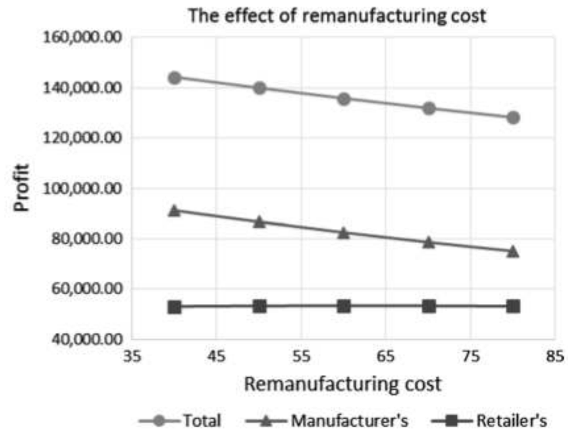

Fig. 14 The effect of remanufacturing cost (c_r) to manufacturer's, retailer's and total profits (integrated scenario)

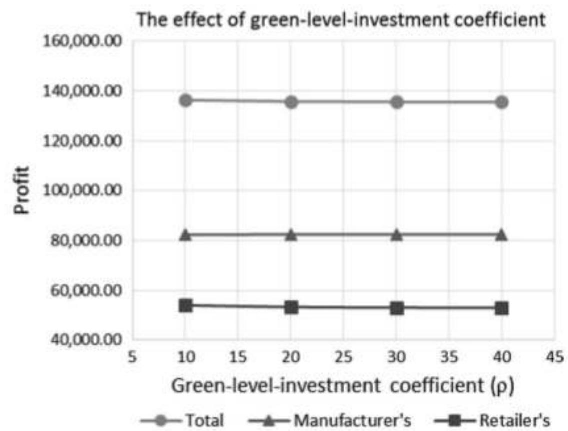

Fig. 15 The effect of green-level-investment coefficient (ρ) to manufacturer's, retailer's and total profits (integrated scenario)

ness to pay, hence identify the magnitude of green-level-demand-expansion coefficient.

- Manufacturer should be careful in increasing green level when the size of green segment is large. This is caused by the higher attractiveness of remanufactured product for green consumers which is responded by increased optimum green level, followed by higher investment cost that erodes manufacturer's profit.
- Manufacturer and retailer are better off when working together in the pricing decision under the integrated scenario with revenue sharing contract, as the total profit gains would be higher compared to the independent scenario. They need to agree on the contracted revenue sharing portion, as well as the lower wholesale prices.
- Price sensitivity plays a significant role in the model, therefore, firms should perform a reliable market survey to better understand the extent of new product's price sensitivity as well as remanufactured product's price sensitivity to decide the optimum green level to attract green consumers.
- Since demand's speed of change is not always better when it is increased, firms should manage the promotion and product immersion such that the increase in demand would not too fast to achieve sufficient demand capacity during the growth period before it decreases fast due to short life-cycle characteristic.
- Under independent scenario, manufacturer should calculate the remanufacturing cost carefully because it would influence the retail prices, both new and remanufactured

product. Higher remanufacturing cost would hurt the firms' profits.

Conclusion

This paper addresses a pricing decision problem for short life-cycle product with price-sensitive demand and green consumers exist. Two supply chain players considered, i.e., manufacturer and retailer, and they decide on wholesale and retail prices of new and remanufactured products with a certain green level. We proposed independently optimized profit scenario under Stackelberg game with manufacturer as the leader, and integrated scenario where the two parties jointly making decision on the prices. The results show that the integrated scenario achieves higher profit compared to the independent scenario, and both players are better off under the integrated decision. We find that the existence of green segment, which is represented by the magnitude of green-level-demand-expansion coefficient, increases the profit of manufacturer and retailer to a certain level. However, there is a certain limit to the magnitude of green-level-demand-expansion coefficient before it erodes manufacturer's profit when the green level is too high. In addition, price sensitivity of new and remanufactured products, demand's speed of change, and remanufacturing cost influence the optimum prices as well as the optimum green level. The proposed models can assist managers in making pricing decisions and assess to what extent the green level should be increased to attract green consumers, how to manage the promotion and product's immersion to the market, and understand the importance of price-sensitivity coefficients. In this study, we have not included the effect of warranty period of the products, which could be significant to consumer's preference to purchase new and remanufactured products. This could be a focus to be explored further. This study can also be extended by considering the return rate in the collection of used product because the quantity and quality of supply of used products are uncertain, so it is important to assess the market-driven collection strategy as opposed to waste stream strategy.

Appendix 1: Proof of Proposition 7

Under the optimum setting in the integrated decision problem:

$$\frac{\partial \Pi_J}{\partial \theta} = \left(\gamma D_r\right)P_r + (-2\rho)\theta + \left(-\gamma D_r c_r\right) = 0 \tag{A1}$$

$$\frac{\partial \Pi_J}{\partial P_r} = \left(bD_n + eD_r\right)P_n + \left(-2cD_r\right)P_r + \left(\gamma D_r\right)\theta + \left(D_r\left(1 + cc_r\right) - bc_m D_r\right) = 0 \tag{A2}$$

The green level can be expressed as

$$\theta_1 = \frac{(\gamma D_r)(P_r - c_r)}{2\rho} \text{ from (A1) and } = \frac{-\left(bD_n + eD_r\right)P_n - 2cD_r P_r - \left(D_r\left(1 + cc_r\right) + bc_m D_r\right)}{\gamma D_r}$$

from (A2)

Therefore, the relations between green level and

(1) Demand capacity for remanufactured product
$\frac{\partial \theta_1}{\partial D_r} = \frac{\gamma(P_r - c_r)}{2\rho} > 0.$ and $\frac{\partial \theta_2}{\partial D_r} = \frac{bD_n P_n}{D_r^2} > 0$

(2) Selling price of remanufactured product
$\frac{\partial \theta_1}{\partial P_r} = \frac{\gamma D_r}{2\rho} > 0$ and $\frac{\partial \theta_2}{\partial P_r} = \frac{2c}{\gamma} > 0$

(3) Remanufacturing cost
$\frac{\partial \theta_1}{\partial c_r} = -\frac{\gamma D_r}{2\rho} < 0$ and $\frac{\partial \theta_2}{\partial c_r} = -\frac{c}{\gamma} < 0$

(qed)

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Pricing decision model for new and remanufactured short life cycle products with green consumers

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