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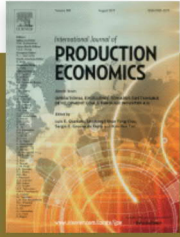
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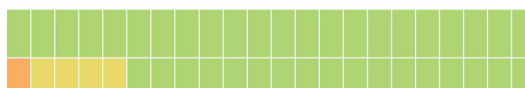
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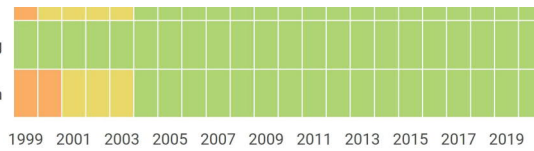


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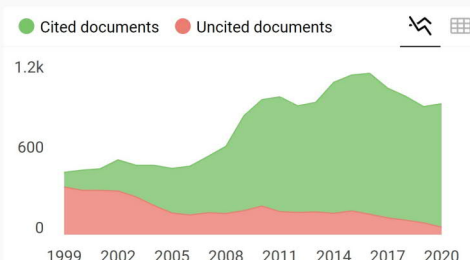
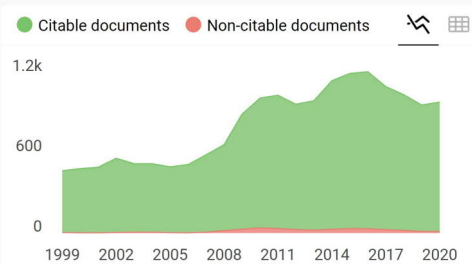
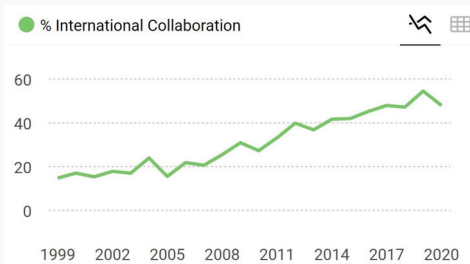
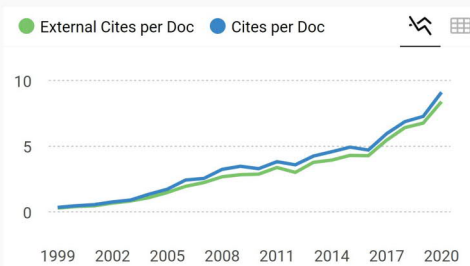
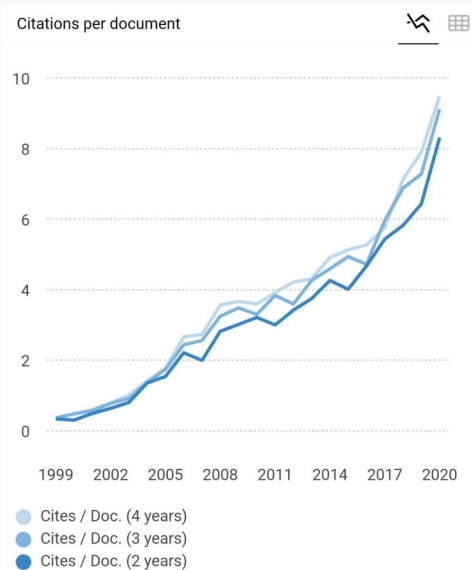
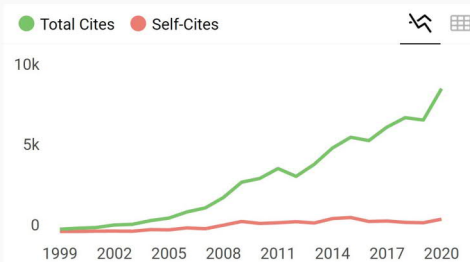
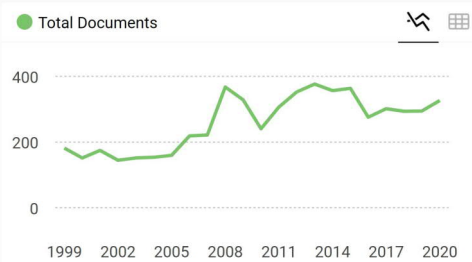
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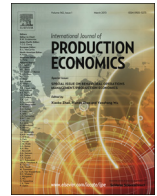
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Pricing decision for new and remanufactured product in a closed-loop supply chain with separate sales-channel



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ABSTRACT

Remanufacturing is a recovery process that transforms a used product into a “like-new” product, which usually comes with a warranty similar to that of the new product. Many manufacturers are concerned that remanufacturing might cannibalize the new product's sales. Recent development shows an increasing trend in selling products through non-traditional channels, such as a manufacturer's direct channel or an e-channel. A pricing decision model is developed for short life-cycle products in a closed-loop supply chain that consists of the manufacturer, retailer, and collector. The new product is sold via traditional retail stores and the remanufactured product is sold via the manufacturer's direct channel. There are two scaling factors introduced in the model: (1) customer acceptance of buying a remanufactured product (reman-acceptance); (2) customer preference for buying a remanufactured product via a direct channel (direct-channel-preference). The results show that implementing a separate channel can improve the total supply chain's profit compared to the single-channel approach. It is also found that the two scaling factors influence both the pricing decisions and profits of supply-chain members.

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1. Introduction

Rapid developments in science and technology have led to faster innovation speed, which provides society with a great deal of excitement but challenges the supply chain as the life cycle of technology-based products shortens (Helo, 2004; Lebreton and Tuma, 2006; Hsueh, 2011). Among technology-based commodities such as mobile phones and computers, there is also increased obsolescence in product function and desirability (Burns, 2010), rendering the earlier product generation to become obsolete more quickly. This phenomenon has led to the disposal of an outdated product at its end of use even when it remains in good condition. Therefore, short life-cycle products contribute significantly to the amount of waste that returns to Mother Earth. Remanufacturing is one option for managing products at the end-of-use phase, transforming a used product into one that is in “like-new” condition. Remanufacturing includes the process of recapturing value added to a material during the manufacturing process (Lund and Hauser, 2010; Charter and Gray, 2008). Several studies have shown

that remanufacturing is a recovery process that provides an opportunity both to support environmental awareness and to comply with waste/take-back legislation while maintaining profitability (Guide and Wassenhove, 2001; Kerr and Ryan, 2001; Savaskan et al., 2004; Ferguson and Toktay, 2006; Kaebernick et al., 2006; Geyer et al., 2007; Lee et al., 2010). When a manufacturer engages in both regular production and remanufacturing, the complexity of supply-chain management increases. The firm must manage both the forward and the reverse channel of the supply chain, integrating the two to form what is now commonly called a closed-loop supply chain (CLSC).

There are at least two important issues when a company sells both new and remanufactured products (hereinafter “reman products”). The first issue involves pricing and the second issue involves sales channels. The question of pricing arises when a company sells new and reman products simultaneously. Whereas the reman products are technically functioning as good as new, it might be sensible to differentiate the price of the two types of products. In such a case, a follow-up question emerges: how different should the price be? It is important to employ an appropriate pricing strategy to address concerns about cannibalization of new-product sales (Atasu et al., 2010) and issues related to the market-expansion effect (Souza, 2013). Few authors have published works that address pricing decisions in remanufacturing

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context; some of those works will be outlined here. Qiaolun et al. (2008) develop a model to obtain the optimal collecting price, the optimal wholesale price and the optimal retail price in a CLSC. Two models were compared and a recommendation was made about who should collect used products. Wei and Zhao (2011) consider retail competition when developing an optimal pricing model in a CLSC system. The author uses both fuzzy and game theory to explore the wholesale price, retail price, and remanufacturing rate. Other authors—including Ferrer and Swaminathan, 2006; Souza, 2009; Lund and Hauser, 2009; Guide and Li, 2010; Shi et al., 2011; Subramanian and Subramanyam, 2011; Chen and Chang, 2013; and Gan et al., 2015—also address pricing issues in a CLSC. However, most these publications only consider a single sales channel (typically brick-and-mortar retail stores) and neglect the fact, as argued by Atasu et al. (2010), that the pricing strategy for new and reman products should focus on market segmentation. The same question will arise in relation to sales channeling. Would the company use the same or different sales channels? Recent development shows that there is an increasing trend of companies selling products through non-traditional channels such as the manufacturer's direct channel (e.g., factory outlet or warehouse stores) and e-channel (online stores). Dell computer sells its reman products via an online channel called the "Dell Outlet" (Kumar and Craig, 2007) while offering new product in both retail and online stores. Similarly, Hewlett-Packard (HP) also sells remanufactured computers in HP's online outlet store; customers cannot buy them in a retail store such as Best Buy, as revealed by Souza (2009). With the rapid growth in Internet usage, manufacturers sell products to consumers not only through traditional retail channels but also through the Internet channel. Sony, Samsung, IBM, and Apple also operate this type of dual channel (Chen and Ku, 2013; Ding et al., 2016).

These pricing and channeling issues in the remanufacturing context are interdependent because the product price decision is affected by the sales channel used. Although some authors have addressed pricing strategy in the dual-channel supply chain, usually they address the forward supply chain only. Huang and Swaminathan (2009) develop a model of pricing strategy in a dual-channel supply chain assuming that demand is deterministic but affected by the price offered. Chen et al. (2013) study the pricing issue in a dual-channel supply chain in which products are substitutable. Although other authors—including Cai et al., 2009; Dan et al., 2012; Zhang et al., 2012; Chen and Ku, 2013; Hsiao and Chen, 2014; and Saha, 2016—also address pricing issues in the dual-channel supply chain, they focus on the forward supply chain. Conversely, there are several studies on CLSC that used the dual channel for collecting used products (Huang, et al., 2013a; Hong et al., 2013b) or selling reman products (Xu and Wu, 2012; Xiong and Yan, 2016). These works however, only consider the reverse supply chain. Many of the abovementioned references also treat both new and reman products as equal and give them the same price. To the best of our knowledge, virtually no study addresses pricing strategy for both new and reman products that use separate sales channels in an integrated CLSC. Because reman products are often perceived as lower quality than new products, customer's willingness-to-pay is likely to be different towards new and reman products (Souza, 2009; Lund and Hauser, 2010; Guide and Li, 2010; Subramanian and Subramanyam, 2012; Chen and Chang, 2013); therefore it is necessary for the model to accommodate the pricing differentiation.

In this study, new and reman products are differentiated and sold via separate channels. The new product is sold via retail channels while the reman products are sold via the manufacturer's direct channel. This study contributes to the pricing strategy by extending pricing decisions in a CLSC using separate sales channels; to the best of our knowledge, this has not been done before.

Two scaling factors characterize the separate sales channel. The first is customer acceptance of buying reman products (hereinafter, reman-acceptance), which shows the customer's willingness to buy reman products. The second factor is the level of customer preference for buying reman products via direct channel (hereinafter, "direct-channel-preference"). Based on the above observation and analysis of the research gaps, this study aims to address the following research questions. First, what is the effect of separating sales channel from the supply chain's profit? Second, what is the profit distribution among the supply chain's members? Third, how do the reman-acceptance level and the direct-channel-preference level influence the optimum results? To answer these questions, a Stackelberg game is applied with the manufacturer as the leader. Various scenarios are explored in relations to pricing of the reman products and the customer's willingness to pay. A numerical example is presented to explore the pricing behavior in various scenarios.

The remainder of this paper is organized as follows. The literature review is described in Section 2. Section 3 describes the problem definition, which includes the CLSC system, the supply chain members involved in the pricing decision, notations, and demand functions. Optimization modeling, including the optimum results and discussions, is performed in Section 4, followed by a numerical example in Section 5. The conclusion and directions for future research are provided in Section 6.

2. Literature review

During the past two decades, a closed-loop supply chain has gained considerable attention in both industry and academia (Guide and Wassenhove, 2009). A critical review of CLSC analytical research can be found in Atasu et al. (2008). The evolution of CLSC research is described in Guide and Wassenhove (2009), which shows a movement from focusing on remanufacturing operations to focusing on the business perspective, i.e., profitable value recovery. Souza (2013) provides a basic modeling framework in CLSC and classifies research into strategic, tactical and operational issues. The most recent review is Govindan et al. (2015), which shows a systematic classification of past research in reverse logistics and the CLSC and provides future research avenues. The subsequent review is provided with a focus on pricing decision in the CLSC and dual-channel supply chain.

2.1. Pricing decision in a closed-loop supply chain

CLSC management involves the reverse supply chain, which is relatively more complex than the forward supply chain. One complicating factor is product return management, which is one of the three key activities in the reverse supply chain (Guide and Wassenhove, 2009); for that reason, many researchers study the problem of pricing a used product (core) and find the optimal collection/ acquisition price in a different setting. Liang et al. (2009) argue that pricing a core is analogous to pricing an option and the core's sales price displays geometric Brownian motion. Pokharel and Liang (2012) consider a stochastic return quantity and quality in finding the optimal price and quantity of cores to be collected. Jena and Sarmah (2014) consider random core demand and three schemes of collection i.e., direct collection by the remanufacturer, indirect collection by the retailer, and coordinated collection between the remanufacturer and the retailer. Xiong et al. (2014) also consider random demand and return, adding uncertainty to the quality of cores with the possibility of lost sales.

From the supply chain perspective, several researchers consider not only the collection but also the distribution of reman products to customers. The pricing problem now focuses on finding the

optimal acquisition price and selling price of the reman products. [Guide et al. \(2003\)](#) investigate factors that influence production planning and control in a CLSC with product recovery under several quality classes of cores; in addition, they determine the optimal prices. [Bakal and Akcali \(2006\)](#) consider the effect of the random recovery yield of cores and [Li et al. \(2009\)](#) extend that work by adding random demand to the consideration. [Vadde et al. \(2006\)](#) consider products with gradual and sudden obsolescence and determine the optimal selling price for reman products. For the pricing problem in a product-recovery facility with several types of output such as reman products, refurbished product, and reusable product of various quality levels, the objective is to find the optimal prices for those outputs. Later, [Mitra \(2007\)](#) classifies two types of output: (1) reman products for quality-conscious buyers; and (2) refurbished products for price-sensitive buyers. [Vadde et al. \(2011\)](#) extend the output type to include as-is reusable, recyclable, poor-quality reusable, and poor-quality recyclable products. In this model, optimal acquisition price is also included.

Although the abovementioned literature focused on the reverse supply chain, there is a broad collection of studies that consider both the forward and reverse supply chains and thus, the pricing problem involves both new and recovered/ reman products. In some cases, new and reman products are considered fully substitutable and sold at the same price. [Ferrer and Swaminathan \(2006\)](#) consider a multi-period scenario under monopoly and duopoly models with deterministic demand and find optimal prices and quantities. [Qiaolun et al. \(2008\)](#) focus on decisions about the core collection price, wholesale and retail prices for the CLSC under three collection scenarios: manufacturer for collecting, retailer for collecting, and third-party for collecting. [Shi et al. \(2011\)](#) consider random demand and returns and determine optimal prices for both brand-new and reman products, along with the acquisition price. [Wei and Zhao \(2011\)](#) take into account two competitive retailers' fuzziness in demands, remanufacturing cost and collection cost to find optimal wholesale and retail prices under centralized and decentralized decision scenarios. [Gao et al. \(2016\)](#) explore the effect of various power structures—i.e., manufacturer Stackelberg, vertical Nash, and retailer Stackelberg—and consider price- and effort-dependent demand to investigate the optimal decisions about pricing, collection effort and sales effort under both centralized and decentralized scenarios. The other studies in the literature address differentiation between new and reman products. [Atasu et al. \(2008\)](#) investigate the optimal price and quantity of new and differentiated reman products by two competitive manufacturers in a two-period model and incorporate the existence of a green segment. [Ferrer and Swaminathan \(2010\)](#) consider monopoly and duopoly under a two-period, a multi-period, and an infinite planning horizon in determining optimal prices and quantities. [Ovchinnikov \(2011\)](#) sets a fixed price for the new product and optimizes the price and quantity of reman products while adding the customer's switching behavior to the model. [Wu \(2013\)](#) focuses on the original equipment manufacturer (OEM) dilemma in determining the level of interchangeability in the product design, which could lower the remanufacturer's cost in cannibalizing the product despite the decrease in the OEM's manufacturing cost. A two-period model is constructed to investigate the OEM's product design decision and both chain members' competitive pricing strategies. [Wu \(2012\)](#) also conducts a parallel study that considers the degree of disassemblability in the OEM's product design. [Chen and Chang \(2013\)](#) consider multi-period dynamic pricing under a constrained core supply. The supply constraint is limited to the availability of end-of-use products in the previous period. This work investigates the pricing behavior over time under several parameter settings—i.e., market property, return rate, and the degree of substitutability between

new and reman products. [Abbey et al. \(2015\)](#) investigate the optimal pricing of new and reman products using a model of consumer preference based on an empirical study, coming up with two segments i.e., a new-product-only segment and an indifferent segment. The model considers the fraction of each segment and a willingness-to-pay function (WTP function) uniformly distributed across $[0,1]$. Several cases are explored, ranging from that of a simple monopolist to a more complex case that involves competing third-party remanufacturers. [Gan et al. \(2015\)](#) consider three members of the supply chain—i.e., manufacturer, retailer, and collector—in determining the optimal wholesale and retail prices for new and reman products along with the optimal acquisition price. The model is constructed to incorporate the effect of the speed of change-in-demand for a short life-cycle product.

Most of the abovementioned papers that develop pricing models for new and reman products consider only the products' optimal prices and overlook the pricing decision in the core collection; the only exceptions are [Qiaolun et al. \(2008\)](#) and [Gan et al. \(2015\)](#). In this paper, all three prices are optimized under a manufacturer Stackelberg and all three members of the supply chain are involved in the game i.e., a manufacturer (who also acts as a remanufacturer), a retailer, and a collector. The differences between this study and [Qiaolun et al. \(2008\)](#) are as follows: (1) in their work, new and reman products are not differentiated; and (2) they use a single sales channel. Compared to [Gan et al. \(2015\)](#), the only difference is in the use of a dual channel instead of a single channel. The introduction of a second separate channel as an outlet for reman products is an effort to focus on market segmentation ([Atasu et al. 2010](#)) because reman products are often perceived as lower quality ([Souza, 2009](#); [Agrawal et al., 2015](#)) and attract the low-end segment more than the high-end segment ([Gan et al., 2014](#)).

2.2. Pricing strategy in the dual-channel supply chain

The pricing strategy for the dual channel in the supply chain has been studied quite extensively. Most of the published works on the subject address the scenario of a single product sold in two different channels, namely, traditional brick-and-mortar retail stores and a manufacturer's direct Internet channel. The literature consists of studies that focus on retail service, disruption, channel structure and selection, and channel coordination.

Retail service in the dual-channel supply chain influences pricing decisions, as discussed in [Hua et al. \(2010\)](#), [Dan et al. \(2012\)](#), [He et al. \(2016\)](#) and [Roy et al. \(2016\)](#). The impact of service quality (which focuses on delivery lead time and customer acceptance of a direct channel) on the manufacturer and retailer's pricing decisions is analyzed in [Hua et al. \(2010\)](#). Customer loyalty to the retail channel is introduced in [Dan et al. \(2012\)](#), in which optimal decisions on retail services and selling prices are investigated under centralized and decentralized dual-channel supply chains. A manufacturer's Stackelberg sequential game is applied to the decentralized approach. It is shown that retail services strongly affect manufacturers and retailers' pricing strategies and profits, whereas the degree of customer loyalty to the retail channel has a significant effect on both retail services and pricing decisions. [He et al. \(2016\)](#) indicate that consumer free riding occurs when consumers enjoy retail service but make lower-price purchases via an e-tailer. This behavior has an impact in that it increases total carbon emissions across the supply chain. [Roy et al. \(2016\)](#) incorporate the retailer's service level and promotional effort into the pricing model under centralized and decentralized scenarios. Pricing strategy in the dual-channel supply chain is also influenced by disruption in both demand and production activity. [Huang et al. \(2012\)](#) and [Huang et al. \(2013b\)](#) study the pricing and production problem in the scenario of demand and production cost

disruption, respectively. The models are each developed to adjust the prices and production plans under their respective disruptions in centralized and decentralized settings. The findings show that optimal pricing decisions are affected by the disruption, with a certain threshold based on customer preference for the direct channel; however, the optimal production plan shows some robustness under disruptions.

Regarding the channel structure, many works investigate the impact of introducing a direct channel as the second distribution channel. Chiang et al. (2003) develop a model that conceptualized the impact of customer acceptance of a direct channel and the use of direct marketing to control the strategic channel. The finding shows that direct marketing can mitigate double marginalization. Tsay and Agrawal (2004) study the implications of channel conflict for the distribution strategy and examines how to adjust the manufacturer-retailer relationship. Chun et al. (2011) study the manufacturer's direct channel strategy to manage the varying needs of consumer segments based on customer heterogeneity and service sensitivity. Xu et al. (2012) extend Chiang et al. (2003) by investigating the effect of price and delivery lead-time decisions on the channel configuration strategy. It is shown that the selection of a channel structure depends on customer acceptance of the online channel and the cost parameters. Hsiao and Chen (2014) consider a case in which not only manufacturer but also the retailer (or both) have the option to operate the Internet channel. Customers are classified into two segments—grocery shoppers and Internet shoppers—that represent channel preference. There are three strategies considered in the pricing decisions: (1) the grocery encroachment strategy; (2) the channel separation strategy with interior optimum; and (3) the channel separation strategy with a corner-optimum solution. Xiao and Shi (2016) consider pricing and channel priority strategies in the presence of a supply shortage caused by a random production yield. The impact of channel coordination is also examined, along with time sequence decisions—i.e., *ex-ante* and *ex-post* production yield. Pricing decisions in dual distribution channels are studied by Cattani et al. (2006), Huang and Swaminathan (2009), Zhang et al. (2012), and Lu and Liu (2013). In a scenario in which a manufacturer opens a direct channel that competes with the traditional channel, Cattani et al. (2006) find that equal-pricing or consistent-pricing strategies that optimize profits for the manufacturer are preferred by the retailer and customers. This strategy is applicable when the Internet channel is significantly less convenient than the traditional channel. Huang and Swaminathan (2009) study the implications for pricing and profit of introducing the Internet channel when demand on a channel is affected by market potential, prices, and degree of substitution across channel. The degree of autonomy for the Internet channel is also investigated in the pricing strategy, considering both monopoly and duopoly settings. Zhang et al. (2012) and Lu and Liu (2013) study pricing decisions in a dual-channel system under different power structures, which are manufacturer Stackelberg, retailer Stackelberg, and vertical Nash. Zhang et al. (2012) focus on duopoly manufacturer and retailer, consider the effects of product substitutability and relative channel status on pricing decisions, and find that no power structure is always the best for all members, whereas Lu and Liu (2013) focus on customer acceptance of channels, determine a threshold at which a channel cannibalizes all retail sales and dominates the distribution system, and find that both supplier and retailer are worse off in the Nash game. Ding et al. (2016) study a hierarchical pricing decision on a dual distribution channel under a Stackelberg game, and find the optimal wholesale price, retail price and direct channel selling price. The results show that operating dual channel is optimal for the manufacturer under some conditions; moreover, consistent pricing and price-matching strategies might not always be optimal for the manufacturer.

Contracts are commonly used to coordinate channels, which can improve the supply chain's profit; on several occasions, it can reduce the channel conflict within a dual-channel supply chain. Cai et al. (2009) investigate the impact of simple price-discount contracts and pricing schemes on the dual-channel competition. The finding shows that the price-discount scheme outperforms the non-contract scenarios and that consistent pricing can decrease the channel conflict. Liu et al. (2010) discuss the joint decision for production and pricing using a principal-agent method under information asymmetry and design two type of contracts i.e., a single contract and a menu of contracts. Chen et al. (2012) examine two coordination schemes that can coordinate the dual-channel supply chain: (1) a manufacturer's contract with a wholesale price and a price for the direct channel; and (2) a complementary agreement consisting of a two-part tariff and negotiated profit sharing, allowing win-win coordination. Chen and Ku (2013) explore the channel strategy by implementing two contracts i.e., the wholesale-price-only contract for the retail channel and the revenue-sharing contract for the Internet channel. Chen Y.C. et al. (2013) consider a retailer that sells not only the manufacturer's product but also a substitute product from another manufacturer. It is shown that improving brand loyalty is profitable for both the manufacturer and the retailer. Additionally, increasing service levels can mitigate channel conflict and increase a manufacturer's profit. Saha (2016) considers channel structures with a traditional retail channel and two manufacturer direct channels, with and without consistent pricing. It is shown that under some conditions the dual channel outperforms the single channel. Furthermore, a coordination mechanism is developed that not only coordinates the dual channel but also outperforms the non-cooperative single retail channel.

This proposed paper incorporates the prominent factor from the above literature of a dual-channel forward supply chain into the proposed model, which involves both new and reman products. The corresponding factor is direct-channel-preference, which is used to identify market segmentation and the tendency to cross channels. Channel separation, which is discussed in Chun et al. (2011) and Hsiao and Chen (2014), is also considered in this model. Chun et al. (2011) identify two segments (i.e., service-sensitive customers and price-sensitive customers), whereas Hsiao and Chen (2014) define two types of customers i.e., grocery shoppers and Internet shoppers. In both models, the offered product is identical, so there is no difference in the supply process. In this work, channel separation is used to identify high-end customers who normally buy new product and low-end customers who prefer reman products at a lower price. There is a need to consider the supply for the reman products, that is, used products collected from customers. Therefore, the pricing decision involves not only manufacturers and retailers but also collector.

2.3. Pricing strategy in a dual-channel closed-loop supply chain

The study on dual-channel closed loop supply chains is quite limited. In the reverse channel, research on sales return in dual channels is conducted by Widodo et al. (2010), who examine the financial benefits for two return scenarios—common return and cross-channel return—under sequential-pricing (Stackelberg) and simultaneous-pricing (Bertrand) games. The results show that the simultaneous process always performs better in terms of total channel profit. Huang et al. (2013a, 2013b) consider dual recycling channels in which a retailer and a third party competitively collect used products. Both centralized and decentralized channel scenarios are analyzed to determine the optimal prices. Furthermore, the competing intensity domain in which the dual channel outperforms the single channel is characterized. Hong et al. (2013) also study hybrid dual-channel collection in three structures:

(1) the manufacturer and the retailer collect the used products; (2) the manufacturer contracts the collection to a retailer and a third party; and (3) both the manufacturer and a third party collect the products. The results show that the manufacturer/retailer hybrid collection channel is the most effective reverse channel structure for the manufacturer. Recent studies also explore the adoption of dual-channel for marketing reman products, as shown in Xu and Wu (2012) and Xiong and Yan (2016). The first paper considers the situation of separate roles in selling reman products in which direct selling on the Internet is managed by the manufacturer and the retailer takes charge of the retail channel. It also studies competition among manufacturer, retailer, and recycling enterprises related to product recycling and finds the optimum direct selling price, retail price and remanufacturing rate. The results show that direct selling has a positive effect in an expanding market but a negative impact in that it attracts demand from retail market. The second paper discusses the implication of channel structures for marketing reman products, i.e., via a manufacturer's owned e-channel or via a third party. The analysis shows that the retailer is better off when the manufacturer chooses its e-channel. He (2015) discusses the dual-supply channel in a CLSC in which the manufacturer receives components from a reliable supplier and from a recycle supplier, who collects used product and remanufactures it into a component equivalent to that of the reliable supplier. The model considers both centralized and decentralized CLSC and determines both optimal production and acquisition price.

The work that is the most similar to ours is Jiang et al. (2010), which investigates pricing strategy in a dual-channel supply chain system with remanufacturing using agent-based modeling to decide optimum quantities and prices. The manufacturer sells new and reman products via retailer and direct Internet channels. The multi-agent supply chain is modeled to include the manufacturer agent, retailer agent, customer agent, finance agent, learning agent, and business agent. The results show that introducing reman products in the direct channel can improve optimal profits. The model parameters observed are customer preference, direct channel cost, and remanufacturing cost. This paper differs from Jiang's: we develop an analytical model that includes several parameters to demonstrate the system behavior and the optimum is found based on the characteristics of the model designed, not on simulation.

In summary, this paper contributes to the literature in three ways. First, the proposed model involves new and reman products that are sold in separate channels. Most of the literature considers the direct channel as a second channel to distribute products to customers. In this work, the direct channel is a means of separating the market segments. The importance of market segmentation when offering both new and reman products has been argued in Atasu et al. (2010) and Abbey et al. (2015). Second, most of the available literature on pricing decisions in a CLSC with dual channels considers manufacturers and retailers, but not collector. In a CLSC, collection plays a significant role because it represents supply constraints. Unlike the forward supply chain in which raw material is considered unconstrained, in a CLSC material is collected from returns or used products. Third, we consider a short life-cycle product in which demand is represented by a time-dependent deterministic function to contain the short life-cycle pattern. This is important because short life-cycle products contribute significantly to exhausting landfills.

3. Problem definition

A CLSC consists of three members: a manufacturer, a retailer, and a collector. The closed loop is initiated by a manufacturer who

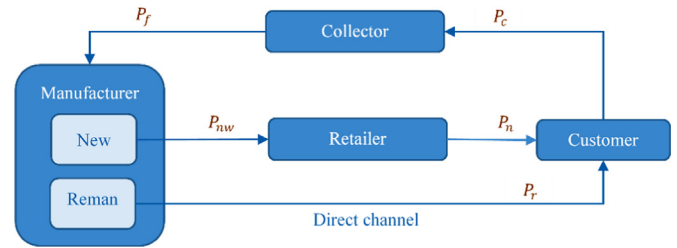


Fig. 1. The closed-loop separate channel system.

makes new products that are sold at a wholesale price, P_{nw} , to the retailer. The new product is then released to the market by the retailer at a retail price P_n . After a certain time, some products reach their end-of-use and become the objects of used-product collection. The used product is acquired by the collector under an acquisition price P_c . It is assumed that the collector only collects used products that meet the required quality level for the remanufacturing process. Therefore, all of the collected returns are transferred to the manufacturer at price P_f , as the input for remanufacturing process. The reman products are then sold via manufacturers' direct channels at a price P_r . The closed-loop separate channel system can be seen in Fig. 1.

In this model, a single product with a short life cycle is considered. After a certain period in the market, the product will become obsolete in terms of both function and desirability. Demand functions are time-dependent and linear in price, representing the short life-cycle pattern along the entire phases for both new and reman products.

There are four time frames considered in this model, as depicted in Fig. 2. In the first interval $[0, t_1]$, only new product is offered to the market. In second and third intervals, i.e., $[t_1, \mu]$ and $[\mu, t_3]$, both new and reman products are offered. The difference between the second and the third intervals is the segments of life-cycle phases for both types. During the second interval, both new and reman products are in the introduction-growth-maturity phases. In the third interval, the new product has entered the decline phase, whereas the reman product has not. In the fourth interval $[t_3, T]$, the manufacturer has stopped producing new product and only offers reman products, which are assumed to be in a phase of decline. The functions that represent these demand patterns are consistent with (Gan et al., 2015). The demand potentials for new and reman products are the demand volumes accumulated over those four time frames, excluding the effect of price sensitivity.

The total demands can be constructed by considering demand potential, price sensitivity, and cross-channel sensitivity. Because the cross-channel is followed by a switch in the customer's choice from buying a new product to buying a remanufactured product, a parameter that represents the scaling factor for reman-acceptance is introduced in the model. These demand functions are similar to those in (Hsiao and Chen, 2014). There are two market segments applied based on Atasu et al., 2010 – i.e., newness-conscious or high-end customers and functionality-oriented or low-end customers.

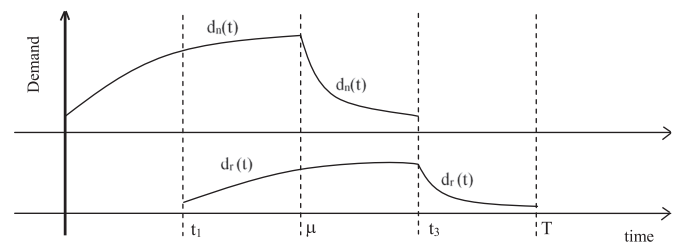


Fig. 2. Demand pattern of a product with gradual obsolescence, over time.

Let v be the customer's valuation of the new product,

- High-end customers buy the new product in retail stores when $v \geq P_n$
- High-end customers buy reman products in the manufacturer's direct channel if $\beta_1 v \geq P_r$ and $\beta_1 v - P_r \geq v - P_n$
- Low-end customers buy reman products in the manufacturer's direct channel if $\beta_2 v \geq P_r$ and $\beta_2 v - P_r \geq v - P_n$.

Low-end customers are considered not interested in buying new product, since the price of new product is most likely higher than the price of reman product (Souza, 2009; Lund and Hauser, 2010; Guide and Li, 2010; Subramanian and Subramanyam, 2012), and the "new" price exceeds those customers' willingness to pay.

The scaling factor for reman products, β_1 , represents the devaluation of reman products in the high-end customer's view because of quality perception. Reman products are often perceived to be inferior to new products; therefore, they have a value in terms of the consumer's willingness to pay (Souza, 2009; Agrawal et al., 2015). For example, let $\beta_1 = 0.7$, which means that a high-end customer values reman products at 70% of the product valuation and would only buy it if the price offered, (P_r), is lower than his/her valuation. Furthermore, when the utility of buying new product is higher ($v - P_n > \beta_1 v - P_r$), a customer would not buy reman products despite the positive utility ($\beta_1 v \geq P_r$).

The scaling factor for direct-channel-preference, β_2 , represents low-end customers' preference to purchase reman products via the direct channel. The customer tends to believe that direct channel store operated by the manufacturer offers a lower price than a retail store because of double marginalization. Therefore, customers who favor functionality over newness would have a stronger preference when reman products are sold via direct channel. Moreover, the green-segment customer prefers reman products. They would find it easier and more convenient to locate the product when it is offered in a different sales channel. However, because new and reman products are not offered together at the same location, the likelihood of cannibalization is low. Customers who intend to buy a new product go to a retail store, where there is a lower risk that they will purchase a reman product instead.

After incorporating the scaling factors, the demand function is constructed for both segments. The product is assumed to be of a high quality such that a low-end customer's willingness to pay is lower than the price of the new product. Therefore, demand for the new product typically comes from high-end customers, whereas demand for reman products mostly comes from low-end customers. There is a channel interplay in which a high-end customer might switch to reman products. Conversely, it is assumed that none of the low-end customers who decided to buy reman products would switch to new products, which are priced higher than those customers' valuation or willingness to pay. Demand for the new product can be expressed as

$$D_n = \begin{cases} \frac{d_{12}}{P_m} \left[P_m - \frac{P_n - P_r}{1 - \beta_1} \right]; & P_r \leq \beta_1 P_n \\ \frac{d_{12}}{P_m} [P_m - P_n]; & \beta_1 P_n \leq P_r \leq \beta_2 P_n \\ 0; & P_r \geq \beta_2 P_n \end{cases} \quad (1a,b)$$

where d_{12} is the cumulative demand potential of new product during $[0, t_3]$ (see Fig. 2). The condition in which " D_n is zero when $P_r \geq \beta_2 P_n$ " represents the absence of channel interplay from D_r to D_n . The condition in which "the price of the new product becomes high enough that high-end customers will not buy it" is implied in (1b), i.e., $P_n = P_m$; and $D_n = 0$.

Demand function for reman products is

$$D_r = \begin{cases} \frac{1}{P_m} \left[d_{34} \left(P_m - \frac{P_r}{\beta_2} \right) + d_{12} \left(\frac{P_n - P_r}{1 - \beta_1} - \frac{P_r}{\beta_1} \right) \right]; & P_r \leq \beta_1 P_n \\ \frac{d_{34}}{P_m} \left[P_m - \frac{P_r}{\beta_2} \right]; & \beta_1 P_n \leq P_r \leq \beta_2 P_n \\ 0; & P_r \geq \beta_2 P_n \end{cases} \quad (2a,b)$$

where d_{34} is the cumulative demand potential of reman products during $[t_1, T]$, as in Fig. 2. The condition in which D_r is zero when $P_r \geq \beta_2 P_n$, represents a condition in which the price of reman products is too high, exceeding low-end customers' valuation or willingness to pay.

The optimal prices are found by applying the Stackelberg pricing game. It starts with the manufacturer as the leader, releasing the wholesale price and remanufactured product's price (reman price). This information is then used by the retailer, along with observation of the market demand, to decide the new product's optimal retail price. The collector observes the demand for the reman products and decides the optimal acquisition price. The collected used products are then transferred to the manufacturer, who further decides the wholesale prices for both the new product sold to the retailer and for the reman price sold via the direct channel.

4. Optimization modeling

The optimization is carried out under a sequential Stackelberg game with the manufacturer as the leader. The objective of the pricing model is to find optimal prices that maximize profits. Because the demand functions are piecewise functions defined by different expressions at different intervals, the price decision must be considered for each interval. Four scenarios are introduced based on the retailer's optimum retail price.

4.1. Retailer's optimization

In Eq. (1), the retailer only sells new product and the sales quantity follows D_n in Eq. (1). There are two intervals for reman price that determine the demand profile: $P_r \leq \beta_1 P_n$ and $\beta_1 P_n \leq P_r \leq \beta_2 P_n$. The retailer's optimization will be conducted for these two intervals.

4.1.1. Retailer's optimization for $P_r \leq \beta_1 P_n$

This interval implies that the price of reman products sold via direct channel is lower than the high-end customer's valuation. Thus, there would be a shift in the high-end customer's preference. A customer who originally intends to purchase a new product ultimately purchases a reman product. The new product demand follows (1a), and the retailer's optimization problem is

$$\text{Max}_{P_n} \Pi_R = \frac{d_{12}}{P_m} \left[P_m - \frac{P_n - P_r}{1 - \beta_1} \right] (P_n - P_{nw}) \quad (3)$$

It is obvious that Π_R is concave in P_n , and thus there is an optimal retail price that maximizes the retailer's profit. Taking the first derivative condition yields

$$\frac{d\Pi_R}{dP_n} = \frac{d_{12}}{P_m} \left[P_m - 2 \frac{P_n - P_r}{1 - \beta_1} + \frac{P_{nw}}{1 - \beta_1} \right] = 0$$

$$P_n^* = \frac{(1-\beta_1)P_m + P_r + P_{nw}}{2} \quad (4)$$

Because $P_r \leq \beta_1 P_n$, then

$$P_r \leq \frac{\beta_1(1-\beta_1)P_m + \beta_1 P_{nw}}{2-\beta_1} \quad (5)$$

Inequality (5) restricts the reman price based on the manufacturer's initial released wholesale price and the customer's maximum willingness to pay.

4.1.2. Retailer's optimization for $\beta_1 P_n \leq P_r \leq \beta_2 P_n$

Under this condition, the price of reman products is higher than the high-end customer's valuation, so that customer is not interested in purchasing reman products. However, the reman price is still lower than the low-end customer's valuation. Demand for new product follows (1b) and the retailer's profit function is

$$\text{Max}_{P_n} \Pi_R = \frac{d_{12}}{P_m} [P_m - P_n] (P_n - P_{nw}) \quad (6)$$

Because Π_R is concave in P_n , there is an optimal retail price that maximizes the retailer's profit and the first derivative condition is

$$\frac{d\Pi_R}{dP_n} = \frac{d_{12}}{P_m} [P_m - 2P_n + P_{nw}] = 0$$

$$P_n^* = \frac{P_m + P_{nw}}{2} \quad (7)$$

This result is the same as the single channel approach in (Gan et al., 2015), in which channel interplay does not exist. In this model, two separate channels are considered with a possibility of channel interplay; in the second interval of the reman price, however, the channel interplay diminishes. This approach is called the channel separation strategy (Hsiao and Chen, 2014).

Furthermore, applying the restriction on reman price based on the interval in D_n gives

$$\beta_1 \left(\frac{P_m + P_{nw}}{2} \right) \leq P_r \leq \beta_2 \left(\frac{P_m + P_{nw}}{2} \right) \quad (8)$$

$$\text{and therefore } \frac{\beta_1(1-\beta_1)P_m + \beta_1 P_{nw}}{2-\beta_1} \leq \beta_1 \left(\frac{P_m + P_{nw}}{2} \right) \quad (9)$$

After determining the optimal retail price based on two different intervals of reman price in the demand function, a restriction on the reman price is found based on the manufacturer's initial released wholesale price and the customer's maximum willingness to pay. These restrictions further create four regions for reman price that leads to four scenarios, as seen in Fig. 3.

- **Scenario I (switching scenario):** $P_r \leq \frac{\beta_1(1-\beta_1)P_m + \beta_1 P_{nw}}{2-\beta_1}$
Demand for the new product follows (1a) and demand for the reman products follows (2a). The optimal retail price is (4). This scenario represents a condition in which the reman price is lower than the high-end customers' valuation of a reman product. Thus, there are customers who switch from buying new products to buying reman products.

- **Scenario II (borderline-switch scenario):**

$$\frac{\beta_1(1-\beta_1)P_m + \beta_1 P_{nw}}{2-\beta_1} \leq P_r \leq \beta_1 \left(\frac{P_m + P_{nw}}{2} \right)$$

This scenario uses the boundary value of reman price, $P_r = \beta_1 P_n$. To encourage channel separation, demand functions follow (1b) for new product and (2b) for reman products. This represents a condition in which reman price is at the lowest value for channel separation because it is at the borderline between high-end customers' switching. The optimal retail price is the corner point

$$P_n^* = \frac{P_r}{\beta_1} \quad (10)$$

- **Scenario III (separation scenario):** $\beta_1 \left(\frac{P_m + P_{nw}}{2} \right) \leq P_r \leq \beta_2 \left(\frac{P_m + P_{nw}}{2} \right)$
This scenario finds an optimum reman price within interior points of $\beta_1 P_n \leq P_r \leq \beta_2 P_n$. Demand for the new product follows (1b) and demand for the reman products follows (2b). The optimal retail price is (7). In this scenario, the reman price is higher than the high-end customers' valuation and thus, the channel separation is strongly supported.
- **Scenario IV (borderline-no-reman scenario):** $P_r \geq \beta_2 \left(\frac{P_m + P_{nw}}{2} \right)$

This scenario uses the other boundary value of the reman price, $P_r = \beta_2 P_n$, where the direct-channel-preference is low such that the reman price is at the borderline of a no-demand situation. Demand for the new product follows (1b) and demand for the reman products follows (2b). The optimal retail price is

$$P_n^* = \frac{P_r}{\beta_2} \quad (11)$$

4.2. Collector's optimization

In the collector's optimization, an increasing return function that depends on the acquisition price is applied, similar to (Qiao-lun et al., 2008). The return function is represented by $\Theta(P_c) = \varphi P_c^\theta D_n$, where $\varphi > 0$ is a constant coefficient and $\theta \in [0,1]$ is the exponent of the power function in the return-rate function, which determines the curve's steepness. This function indicates that collected returns are only a portion of a new product's sales and the portion (or return rate) increases as the acquisition price increases. Therefore, the collector should determine optimal acquisition price that are high enough to acquire the needed

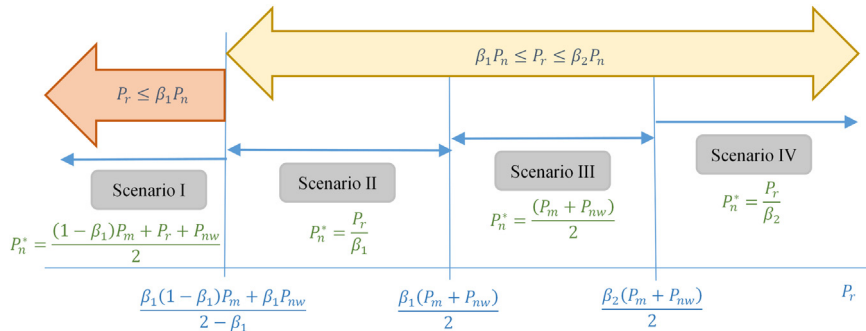


Fig. 3. Reman price regions that lead to four scenarios.

quantity of returns, but not high enough to reduce the collector's profit. A balanced quantity is applied throughout the supply chain, so the collector only acquires as much as the demand for reman products. It is assumed that the collector would only collect used product that meets the quality criteria of the remanufacturing process. Another assumption is made for the number of remanufacturing processes applied to a product. The used product collected should be originated from new product, which suggests only a single or one-time remanufacturing process for each product. A parameter is introduced here, c , unit collecting cost. The optimization is carried out for all scenarios.

4.2.1. *Scenario I: $P_r \leq \frac{\beta_1(1-\beta_1)P_m + \beta_1 P_{nw}}{2-\beta_1}$*

The collector's optimization problem is

$$\text{Max}_{P_c} \Pi_c = \varphi P_c^{\theta} d_{12} \left[P_m - \frac{P_n - P_r}{1-\beta_1} \right] (P_f - P_c - c) \quad (12)$$

The collector's profit function is concave and the optimum collecting price is

$$P_c^* = \frac{\theta(P_f - c)}{(\theta+1)} \quad (13)$$

Applying balanced quantity yields

$$\frac{1}{P_m} \left[d_{34} \left(P_m - \frac{P_r}{\beta_2} \right) + d_{12} \left(\frac{P_n - P_r}{1-\beta_1} - \frac{P_r}{\beta_1} \right) \right] = \varphi P_c^{\theta} d_{12} \left[P_m - \frac{P_n - P_r}{1-\beta_1} \right] \quad (14)$$

Substituting P_c with (13),

$$P_f^* = \left[\frac{d_{34} \left(P_m - \frac{P_r}{\beta_2} \right) + d_{12} \left(\frac{P_n^* \beta_1 - P_r}{\beta_1(1-\beta_1)} \right)}{\varphi d_{12} \left(P_m - \frac{P_n^* - P_r}{1-\beta_1} \right)} \right]^{\frac{1}{\theta}} \cdot \frac{\theta+1}{\theta} + c \quad (15)$$

with P_n as in (4).

4.2.2. *Scenario II: $\frac{\beta_1(1-\beta_1)P_m + \beta_1 P_{nw}}{2-\beta_1} \leq P_r \leq \beta_1 \left(\frac{P_m + P_{nw}}{2} \right)$*

The collector's optimization problem in this scenario is

$$\text{Max}_{P_c} \Pi_c = \varphi P_c^{\theta} d_{12} (P_m - P_n) (P_f - P_c - c) \quad (16)$$

The collector's profit function is concave and the optimum collecting price is the same as (13). The optimal acquisition price in scenario II is the same as in scenario I because the demand function does not contribute to fulfilling the first derivative condition. Furthermore, applying a balanced quantity gives

$$\frac{d_{34}}{P_m} \left[P_m - \frac{P_r}{\beta_2} \right] = \varphi P_c^{\theta} d_{12} [P_m - P_n] \quad (17)$$

Substituting P_c with (13) and P_n with (10),

$$P_f^* = \left[\frac{d_{34} \left(P_m - \frac{P_r}{\beta_2} \right)}{\varphi d_{12} \left(P_m - \frac{P_r}{\beta_1} \right)} \right]^{\frac{1}{\theta}} \cdot \frac{\theta+1}{\theta} + c \quad (18)$$

4.2.3. *Scenario III: $\beta_1 \left(\frac{P_m + P_{nw}}{2} \right) \leq P_r \leq \beta_2 \left(\frac{P_m + P_{nw}}{2} \right)$*

The collector's optimization problem in this scenario is the same as scenario II, which is given in (16), so is the balanced quantity as in (17). Therefore, the optimal acquisition price is (13). Substituting P_c with the optimum and P_n with (7)

$$P_f^* = \left[\frac{d_{34} \left(P_m - \frac{P_r}{\beta_2} \right)}{\varphi d_{12} \left(\frac{P_m - P_{nw}}{2} \right)} \right]^{\frac{1}{\theta}} \cdot \frac{\theta+1}{\theta} + c \quad (19)$$

4.2.4. *Scenario IV: $P_r \geq \beta_2 \left(\frac{P_m + P_{nw}}{2} \right)$*

In the fourth scenario, the collector's optimization problem is also the same as scenario II, which is given in (16), along with the balanced quantity, as in (17). Therefore, the optimal acquisition price is (13) and by using P_n as in (11), the transfer price can be expressed as

$$P_f^* = \left[\frac{d_{34}}{\varphi d_{12}} \right]^{\frac{1}{\theta}} \cdot \frac{\theta+1}{\theta} + c \quad (20)$$

4.3. Manufacturer's optimization

The optimal prices determined by the retailer and the collector become inputs in the manufacturer's optimization to maximize her profit. The optimization problem is

$$\text{Max}_{P_{nw}, P_r} \Pi_M = D_n(P_{nw} - c_{rw} - c_m) + D_r(P_r - P_f - c_r) \quad (21)$$

where c_{rw} is the unit raw material cost for producing new product, c_m is the unit manufacturing cost for producing new product, and c_r is the unit remanufacturing cost for producing and selling reman products in the manufacturer's direct channel.

4.3.1. *Scenario I: $P_r \leq \frac{\beta_1(1-\beta_1)P_m + \beta_1 P_{nw}}{2-\beta_1}$*

In the manufacturer's optimization, reman price P_r is a decision variable and therefore, it is necessary to impose its restriction on each scenario. The restrictions become the constraints to the optimization problem.

The optimization problem in scenario I is then stated as follows:

$$\begin{aligned} \text{Max}_{P_{nw}, P_r} \Pi_M &= \frac{d_{12}}{P_m} \left[P_m - \frac{P_n^* - P_r}{1-\beta_1} \right] (P_{nw} - c_{rw} - c_m) \\ &+ \frac{1}{P_m} \left[d_{34} \left(P_m - \frac{P_r}{\beta_2} \right) + d_{12} \left(\frac{P_n^* - P_r}{1-\beta_1} - \frac{P_r}{\beta_1} \right) \right] \\ &(P_r - P_f^* - c_r) \end{aligned} \quad (22)$$

subject to.

(1) Reman price restriction for scenario I: $P_r \leq \frac{\beta_1(1-\beta_1)P_m + \beta_1 P_{nw}}{2-\beta_1}$.

(2) Supply constraint:

$$d_{12} \left[P_m - \frac{P_n^* - P_r}{1-\beta_1} \right] \geq \left[d_{34} \left(P_m - \frac{P_r}{\beta_2} \right) + d_{12} \left(\frac{P_n^* - P_r}{1-\beta_1} - \frac{P_r}{\beta_1} \right) \right].$$

(3) Lower bound: $P_{nw} \geq P_{nw_initial}$; $P_r \geq P_{r_initial}$.

$P_{nw_initial}$ and $P_{r_initial}$ are the initial wholesale and reman price released to the retailer and collector.

(4) Upper bound: $P_{nw} \leq (1-\beta_1)P_m + P_r$.

where P_n^* and P_f^* are expressions given in (4) and (15), respectively.

This optimization problem is solved using the computational approach because it becomes too complex for the analytical approach and for finding closed-form solutions.

4.3.2. *Scenario II: $\frac{\beta_1(1-\beta_1)P_m + \beta_1 P_{nw}}{2-\beta_1} \leq P_r \leq \beta_1 \left(\frac{P_m + P_{nw}}{2} \right)$*

In this scenario, $P_n^* = P_r/\beta_1$, the manufacturer's profit function becomes

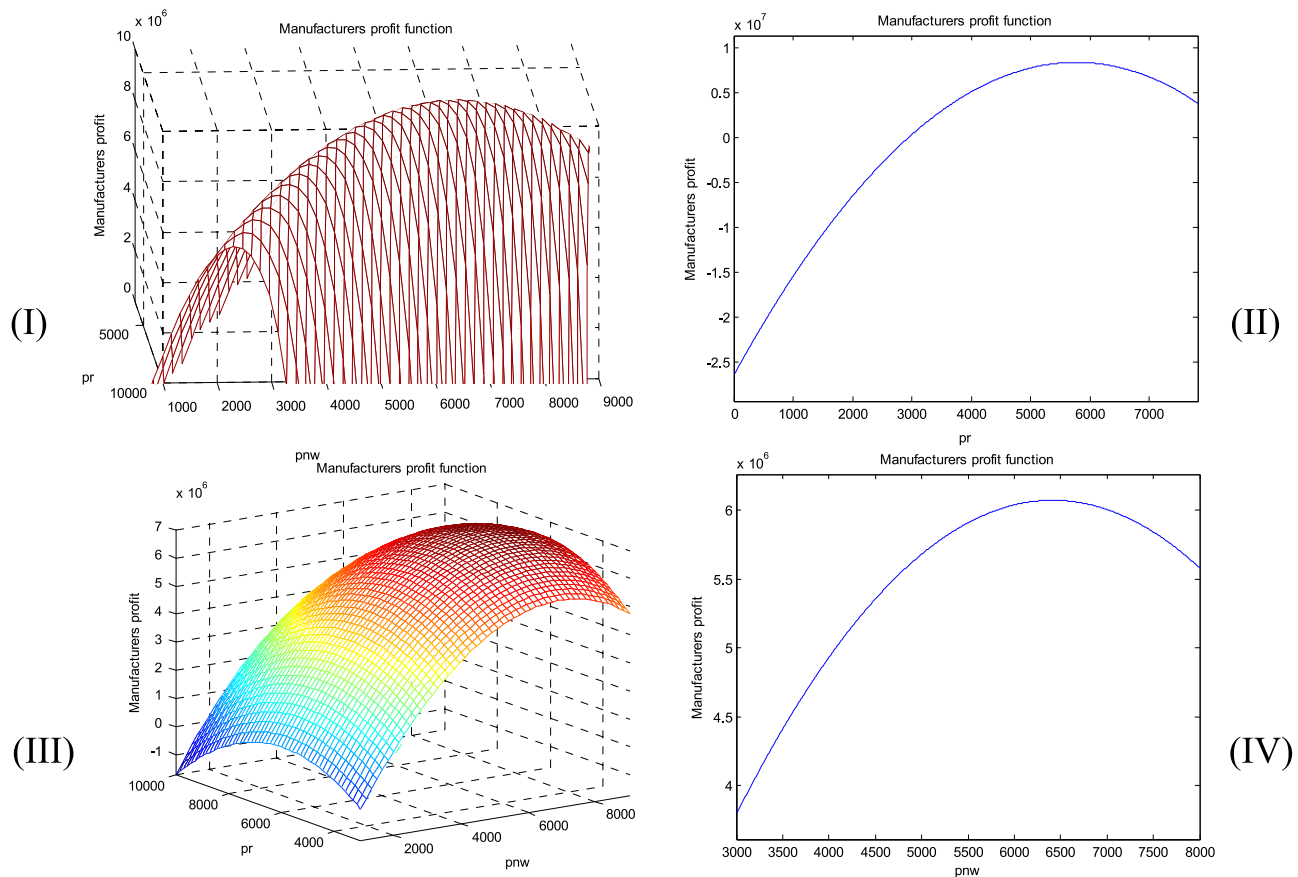


Fig. 4. Manufacturer's Profit Function for Scenarios I, II, III, IV.

Table 1
Numerical example for various scenarios.

	Scenario I	Scenario II	Scenario III	Scenario IV	Single channel (Gan et al., 2015)
β_1	0.80	0.70	0.60	0.50	
β_2	0.90	0.80	0.70	0.60	
P_n	7700.00	8571.43	9500.00	10,000.00	9889.78
P_r	6346.70	5647.74	5673.33	5597.54	8318.83
P_{nw}	7120.05	6888.65	6911.08	6658.48	7018.45
P_c	729.03	366.10	389.80	248.25	422.04
P_f	1870.49	989.10	1046.67	702.89	1124.96
Π_M	4,948,745.78	4,090,846.09	3,291,706.88	2,714,894.15	2,391,233.07
Π_R	505,607.36	961,102.81	1,078,173.11	1,113,281.64	1,246,142.45
Π_C	205,065.44	186,107.37	150,977.65	56,087.71	145,869.03
Total profit	5,659,418.58	5,238,056.27	4,520,857.64	3,884,263.50	3,783,244.55
D_n	871.81	571.14	416.46	333.17	351.53
D_r	196.90	390.67	308.02	211.20	150.73

$$\Pi_M = \frac{d_{12}}{P_m} \left[P_m - \frac{P_r}{\beta_1} \right] (P_{nw} - c_{rw} - c_m) + \frac{d_{34}}{P_m} \left[P_m - \frac{P_r}{\beta_2} \right] (P_r - P_f^* - c_r)$$

$$\begin{aligned} \text{Max}_{P_{nw}, P_r} \Pi_M &= \frac{d_{12}}{P_m} \left[P_m - \frac{P_r}{\beta_1} \right] (P_{nw} - c_{rw} - c_m) \\ &+ \frac{d_{34}}{P_m} \left[P_m - \frac{P_r}{\beta_2} \right] (P_r - P_f^* - c_r) \end{aligned} \quad (23)$$

It is obvious that the optimization process would seek the largest possible value for P_{nw} to maximize the profit function. Therefore, the optimum must occur on the boundary, i.e.,

$$P_r = \frac{\beta_1(1-\beta_1)P_m + \beta_1 P_{nw}}{2-\beta_1}$$

The optimization problem in scenario II becomes

subject to

- (1) Reman price restriction in scenario II that provide the largest P_{nw} :

$$P_r = \frac{\beta_1(1-\beta_1)P_m + \beta_1 P_{nw}}{2-\beta_1}$$

$$(2) \text{ Supply constraint: } d_{12} \left[P_m - \frac{P_r}{\beta_1} \right] \geq d_{34} \left[P_m - \frac{P_r}{\beta_2} \right].$$

$$(3) \text{ Upper bound: } P_{nw} \leq P_m \text{ where } P_f^* \text{ is the expression given in (18).}$$

Similar to scenario I, because of its complexity, this optimization problem is solved through the computational approach.

$$4.3.3. \text{ Scenario III: } \beta_1 \left(\frac{P_m + P_{nw}}{2} \right) \leq P_r \leq \beta_2 \left(\frac{P_m + P_{nw}}{2} \right)$$

In scenario III, $P_n^* = \frac{P_m + P_{nw}}{2}$, hence the optimization problem becomes

$$\begin{aligned} \text{Max}_{P_{nw}, P_r} \Pi_M &= \frac{d_{12}}{P_m} \left[\frac{P_m - P_{nw}}{2} \right] (P_{nw} - c_{rw} - c_m) \\ &+ \frac{d_{34}}{P_m} \left[P_m - \frac{P_r}{\beta_2} \right] (P_r - P_f^* - c_r) \end{aligned} \quad (24)$$

subject to.

$$(1) \text{ Reman price restriction for scenario III: } \beta_1 \left(\frac{P_m + P_{nw}}{2} \right) \leq P_r \leq \beta_2 \left(\frac{P_m + P_{nw}}{2} \right).$$

$$(2) \text{ Supply constraint: } d_{12} \left[\frac{P_m - P_{nw}}{2} \right] \geq d_{34} \left[P_m - \frac{P_r}{\beta_2} \right].$$

$$(3) \text{ Upper bound: } P_{nw} \leq P_m, \text{ where } P_f^* \text{ is the expression given in (19).}$$

$$4.3.4. \text{ Scenario IV: } P_r \geq \beta_2 \left(\frac{P_m + P_{nw}}{2} \right)$$

In this scenario, reman price is high but remains within the customer's willingness to pay. The model also takes demand function (1b) for new product and demand function (2b) for reman products.

Because in scenario IV $P_n^* = P_r/\beta_2$, the manufacturer's profit function becomes

$$\Pi_M = \frac{d_{12}}{P_m} \left[P_m - \frac{P_r}{\beta_2} \right] (P_{nw} - c_{rw} - c_m) + \frac{d_{34}}{P_m} \left[P_m - \frac{P_r}{\beta_2} \right] (P_r - P_f^* - c_r)$$

Because the profit function is linearly increasing in P_{nw} , the optimization process seeks the largest possible value for P_{nw} to obtain maximum profit. Therefore, the optimum must occur on the boundary, i.e., $P_r = \beta_2 \left(\frac{P_m + P_{nw}}{2} \right)$.

Supply constraint can be omitted because $\frac{d_{12}}{P_m} \left[P_m - \frac{P_r}{\beta_2} \right] \geq \frac{d_{34}}{P_m} \left[P_m - \frac{P_r}{\beta_2} \right]$ implies $d_{12} \geq d_{34}$, which is always true.

The optimization problem in scenario IV becomes

$$\begin{aligned} \text{Max}_{P_{nw}} \Pi_M &= \left(\frac{P_m - P_{nw}}{2P_m} \right) \left[d_{12} (P_{nw} - c_{rw} - c_m) \right. \\ &\left. + d_{34} \left(\beta_2 \left(\frac{P_m + P_{nw}}{2} \right) - P_f^* - c_r \right) \right] \end{aligned} \quad (25)$$

subject to upper bound: $P_{nw} \leq P_m$, where P_f^* is the expression given in (20).

5. Numerical example

Let the demand potential's parameters for new product and reman products be the same as the numerical example in the single-channel approach set forth in (Gan et al., 2015). The selling horizon is one year and divided into four periods in which $t_1 = 1$, $\mu = 2$, $t_3 = 3$, and $T = 4$ in trimester units. The unit raw material cost for new product $c_{rw} = 1500$, unit manufacturing cost $c_m = 1000$, unit remanufacturing cost $c_r = 800$, and unit collecting cost $c = 100$. The maximum price is $P_m = 12,000$. Price and costs are given in thousands of rupiah. Return rate parameters are $\varphi = 0.01$, and $\theta = 0.7$. Reman-acceptance (β_1) and the scaling factor for direct-

channel-preference (β_2) for scenarios I, II, III, IV are (0.8, 0.9), (0.7 and 0.8), (0.6 and 0.8), and (0.5 and 0.6), respectively.

Because the manufacturer's optimization is solved using the computational approach, the existence and uniqueness of the solution are investigated through the plotting approach, which is shown in Fig. 4 for various scenarios.

The computational results are given in Table 1. In the separate-channel system, the manufacturer's profit is much higher than that of retailer because the manufacturer sells both new and reman products, whereas the retailer only sells new products.

From the results in Table 1, it is shown that applying the separate channel can improve the total supply-chain profit compared to the model that adopts the single-channel approach (Gan et al., 2015). In the single-channel model, the optimum reman product's price is quite high because it is offered through the same channel as the new product, i.e., a retail store. Therefore, double marginalization exists and it both increases the reman product's price and decreases demand.

The scaling factor that represents reman-acceptance, β_1 , significantly influences pricing decisions and the profits of the supply-chain members. It can be observed that lower reman-acceptance leads to higher retail price. This is understandable because high-end customers are reluctant to purchase reman products (Atasu et al., 2010), and the retailer responds by increasing the retail price. However, a higher retail price decreases the demand for a new product. Although the retailer's profit is improving, the manufacturer's profit is hurt by the small quantity of new product. Despite the potential profit gain that comes from reman products, manufacturer must consider the supply constraint that limit the quantity of those products.

When reman-acceptance is high, optimization likely falls into the first scenario, which demonstrates the best performance in terms of total supply chain profit. Indeed, unlike the retailer, the manufacturer receives the most benefit from this scenario. As reman-acceptance increases, the likelihood of high-end customers switching from new to reman also increases. The retailer responds by lowering the retail price to attract more high-end customers and deter switching. As the Stackelberg leader, however, the manufacturer optimizes her profit after receiving the retailer's pricing decision. The manufacturer finds an optimal reman price that is higher than the initial reman price released to the retailer. Therefore, the demand decreases for reman products but increases for new products. Because the retailer has already set the new product's price relatively low, her profit is relatively low, even though it is higher than in the initial condition, when the demand for the new product is low. Collectors can also benefit from this scenario, but not in a consistent way. In this scenario, demand for reman products is high during the retailer's optimization. Consequently, the response is a high acquisition price followed by a high transfer price. Although the first scenario performs best, it has a limitation. If reman-acceptance is very high, the reman product's demand can be so high that a supply constraint results and the collector cannot acquire enough used product for the remanufacturing process. This is a limitation of our model. Therefore, it is our intention to further explore a pricing strategy that includes green segment consideration, in which the reman price can be set higher than that of the new product, along with a condition in which there is a switch from the reman product to the new product.

Scenarios II, III, and IV support the channel separation strategy, in which the effect of the channel interplay is minimized. Scenario II is implemented when the reman price lies at the borderline of switching from new to reman. When the reman price is quite high relative to high-end customers, channel separation is naturally formed; this is captured in scenario III. Scenario IV is applied to a situation in which both reman-acceptance and direct-channel-

preference is low, whereas reman price is quite high but remains at the borderline of the no-demand situation. The model would respond with a pricing decision that placed new and reman products based on the channel selection. There is a threshold for reman-acceptance under which it becomes unprofitable to sell reman products.

The collector's optimum result does not follow the reman-acceptance trend. As reman-acceptance decreases, the acquisition price and collector's profit changes inconclusively. Scenario I provides the collector with the best result. This can be explained by the high demand for reman products during the retailer's optimization, to which the collector responds by deciding to collect a high number of returns. The attempt to collect sufficient used product is achieved by setting an acquisition price that is high enough to interest customers in selling their end-of-use products. Consequently, a higher acquisition price is followed by a higher transfer price and thus, a higher collector's profit.

Scenario III is the case that is the most similar to the single-channel model (Gan et al., 2015). In that model, cannibalization is not considered even though new and reman products are sold through the same channel. The term cannibalization refers to a situation in which a customer initially plans to buy a new product, but ultimately buys a reman product because such products have become more attractive. This phenomenon is usually caused by the attractiveness of low price among low-end or functionality-oriented customers. In this separate channel system, scenario III is only applied when reman price falls within a certain interval between high-end customers' valuation of reman products and low-end customers' willingness to pay.

Scenario IV works best for the retailer because it is implemented in a situation in which reman-acceptance is low. Therefore, the retailer can set a higher retail price. Despite the lower demand caused by high retail price, the retailer's profit is higher than in the other scenarios.

The effect of scaling factor for direct-channel-preference (β_2) can also be investigated through the results in Table 1. Scenario IV would be effective on lower β_2 . In this case, retail price is high and reman price is low compared to scenarios I and III. Because the demand for new and reman products is also low, the total supply chain's profit is depleted. This is understandable because scenario IV represents the strategy for a situation that is very close to no demand. However, the collector suffers the most. When the retailer can continue to benefit from a high retail price despite low demand for the new product, manufacturers still obtain revenue from selling both products, the collector is hurt by reman products' low demand and low price, which means low transfer price. As for the effect of β_2 within the same scenario, it can be observed that the lower the β_2 , the lower the reman price, acquisition price, and transfer price; the retail price and the wholesale price do not change. However, when different scenario is applied, lower β_2 leads to a higher retail price.

The optimization model and the numerical experiment have shown that the application of a separate sales-channel system in which new and reman products are sold through different channels can improve total supply-chain profit. Because the optimums in this model are influenced by the level of reman-acceptance and direct-channel-preference, managers should assess those parameters to apply the best scenario. The lower the reman-acceptance, the lower the manufacturer's profit. Therefore, the manufacturer needs to improve the marketing strategy to increase reman-acceptance. In addition, a decrease in direct-channel-preference would reduce manufacturers and collectors' profits. Marketing strategy and joint promotion between manufacturers and collectors can increase direct-channel-preference. This is possible, for example, by offering a trade-in program or rebate for customers who return their end-of-use product in the manufacturer's direct channel.

6. Conclusion and future research

This paper presents pricing decisions for new and differentiated reman products in a CLSC with a separate sales channel has been presented in this paper. The pricing model is developed under four scenarios with respect to the reman price and evaluate two parameters: (1) reman-acceptance (β_1), which represents high-end customers' willingness to switch purchases from new to reman products; and (2) direct-channel-preference (β_2), which represents customers' willingness to purchase reman products offered through direct channels. The models enrich the literature on pricing decisions in the CLSC in which channel separation for new and reman products is introduced. This proposed model is the first to implement separate sales channels and differentiate prices for new and reman products.

The numerical experiments demonstrate several important observations. *First*, the separate sales channel results in higher total supply-chain profit compared to the single-channel approach. This implies that in a situation in which the manufacturer is capable of operating a direct channel, it is advisable to sell new and reman products via different channels to target the correct segment in each channel. In this way, market segmentation is recognizable to address managers' concern that lower-priced reman products could cannibalize the sales of new products (Atasu et al., 2010). *Second*, the best scenario for the supply chain overall is not necessarily the best for each individual member. As noted in the discussion above, the highest total profit for the supply chain is achieved when scenario I is implemented, that is, when high-end customers are willing to switch their purchases from new to reman products. However, this highest total profit is at the expense of the retailer, whose profit is lowest. The increase in profit is very much pooled with the manufacturer. This implies the need for the supply chain to design an incentive mechanism for each member to ensure that the maximum profit is obtained without making any party worse off. *Third*, with respect to the scaling factors, the reman-acceptance factor significantly influences both pricing decisions and the supply-chain members' profits. The lower the reman-acceptance, the higher the retail price; thus, new-product demand decreases and the manufacturer's profit decreases. The direct-channel-preference, however, is most effective in the borderline no-reman scenario. The lower the direct-channel-preference, the lower the reman, acquisition, and transfer prices; however, the retail and wholesale prices do not change within the same scenario. Manufacturer and collector's profits decrease with direct-channel-preference.

Because the optimums in this model are influenced by the level of reman-acceptance and direct-channel-preference, managers should assess those parameters to apply the best scenario. The lower the reman-acceptance, the lower the manufacturer's profit. Therefore, the manufacturer must improve its marketing strategy to increase reman-acceptance. In addition, a decrease in direct-channel-preference would decrease the profits of both manufacturers and collectors. Marketing strategy and joint promotion between manufacturers and collectors can increase direct-channel-preference, for example, through a trade-in program or rebate for customers who return their end-of-use products and purchase reman products in the manufacturer's direct channel.

Obviously, the pricing decision is strategic in any business, and it is even more important when companies offer both new and reman products. The issue of cannibalization and the sufficiency of cores as inputs for the reman process need sufficient attention. Many follow-up studies could emerge from this paper. First, the green segment is not considered here. When the reman price is quite high, the model leads to a no-demand situation. A future study that attempts to refine the demand function to incorporate segments of customers who are willing to purchase reman

products even if they are highly priced would be desirable. Second, this paper assumes a balanced quantity throughout the selling horizon; therefore, the dynamics of product quantity, inventory and salvage consequences are unexplored here. Third, this model uses the assumption of deterministic demand, which deviates from reality in which demand normally follows a random function. These limitations warrant the need for further studies in this important field.

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