Flexible Services and Manufacturing Journal (2021) 33:425–456
https://doi.org/10.1007/s10696-020-09379-3

Production-quality policy for a make-from-stock remanufacturing system

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Abstract

Remanufacturing capacities are constrained by the collected amount of end-of-life (EOL) products resulting in the make-from-stock model for remanufacturing industries. Remanufacturers may select quality choices in a strategic manner to improve their remanufacturing capacities. Thus, we examine a Cournot duopoly in which an original equipment manufacturer (OEM) sells new products and an independent remanufacturer (IR) remanufactures EOL products, and we determine the production quantities of low- and high-quality remanufactured products. The IR can select pure low-quality, pure high-quality, or mixed-quality policies. We formulate the dynamics between the OEM and IR in a two-period game, solve for the firms' equilibrium quantities through dynamic programming, and derive the conditions of the remanufacturing-quality policies. Furthermore, we characterize the firms' equilibrium decisions and analyze the parametric effects on profits, consumer surplus, and social welfare. When the availability of EOL products is sufficient, a high-quality policy is the dominant strategy for the IR and is also beneficial to both the OEM and consumers in most cases. However, when the amount of EOL products is not sufficient, the IR may choose to reduce the average quality level to obtain ample capacity; this situation is beneficial to consumers but harmful to the OEM.

Keywords Supply chain management · Quality · Remanufacturing capacity · Cournot game · Make from stock

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Electronic supplementary material The online version of this article (https://doi.org/10.1007/s10696-020-09379-3) contains supplementary material, which is available to authorized users.

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1 Introduction

Strategically allocating production to different manufacturers or producing units with different quality levels is a commonly adopted practice among many firms to improve their productivity and profitabilities. For example, Apple Inc. commonly allocates component manufacturing and assembly to different manufacturers; e.g., a battery from Samsung and Sunwoda, a camera from Qualcomm and Sony, CPU chips from TSMC and Samsung, and assembly by Foxconn and Pegatron (Apple Inc. 2018). In 2015, Apple allocated the production of A9 chips for its iPhone 6s/6s+ to two different manufacturers, TSMC and Samsung; however, some hardware specialists reported that these two manufacturers' manufacturing processes lead to the different battery consumption performances, generally referred to as different quality levels (Williams 2015). These reports significantly affected consumers' purchasing behavior, leading them to select specific serial numbers of the iPhone 6s/6s+. Moreover, many manufacturers, e.g., electronic appliance manufacturers, satisfy demand quantities by dispersing their capacities among different production lines or factories that possess different production qualities because of equipment capabilities or operator skills. Consequently, some consumers will select products with specific serial numbers or countries of origins (Elliott and Cameron 1994). Accordingly, manufacturers will allocate greater quantities of high-end products to lines or factories with superior quality levels such that consumers perceive higher average quality levels of the high-end products. However, most consumers are unable to distinguish differences in quality for the same model of a product but make purchase decisions based on information regarding general evaluations of product qualities. Therefore, firms must carefully allocate their production quantities of products with different quality levels in the trade-off between production capacities and consumers' perceptions of quality levels.

Consumers desire low-priced functional products, and increased environmental awareness has accelerated the development of the remanufacturing industry. Remanufacturing is a process for restoring end-of-life (EOL) products produced by original equipment manufacturers (OEMs) to near-new conditions through replacement and rebuilding processes. Thus, the reduction in raw materials required and production procedures allow many remanufactured products to have smaller environmental footprints and lower production costs than new products. For example, Research and Markets (2020) found that the automotive parts remanufacturing market is anticipated to hit US $58.8 billion at a compound annual growth rate of 6.6% between 2017 and 2025. Many empirical studies (e.g., D'Souza et al. 2007; Subramanian and Subramanyam 2012; Abbey et al. 2015; Joshi and Rahman 2015) have found that both sales prices and consumer quality perception are significant factors affecting the purchasing of remanufactured products. Specifically, Subramanian and Subramanyam (2012), Abbey et al. (2015), and Parker et al. (2015) found that consumers generally assign lower reservation prices to remanufactured products than to new products because of uncertainty regarding quality even when controlling for warranty length. Abbey et al. (2015) indicated that remanufactured products currently only account for approximately 5–10% of the consumer market because their sales are hindered by a lower quality perception. In this regard, quality in remanufacturing is a significant issue in practice and for research.

Because remanufacturing follows a “make from stock” model (Fleischmann et al. 2005; Galbreth and Blackburn 2006), the remanufacturing capacity is associated with the amount of EOL products and the desired quality level after remanufacturing (Ferguson et al. 2009). Specifically, remanufacturers sort EOL products in variable conditions before the restoration process, after which they determine which products should be remanufactured and which should be scrapped based on their desired quality levels (Galbreth and Blackburn 2006, 2010; Wei et al. 2015). Therefore, when a remanufacturer selects a higher quality level, fewer EOL products qualify for remanufacture, and the remanufacturing capacity decreases. In contrast, reducing the quality level for a greater remanufacturing capacity intensifies competition between remanufacturers and OEMs, hurting profits but potentially benefiting consumers because of lower prices (Melumad and Ziv 2004). As a result, remanufacturers face a dilemma when determining their production quantities and quality levels. Although endogenous quality choices have been widely investigated in the literature regarding traditional supply chains, studies considering strategic quality policies and the relationship between capacity and quality policies and remanufacturing are limited. Therefore, in this study, we examine whether an independent remanufacturer (IR) can control the average quality level of its remanufactured products by allocating production capacities between low- and high-quality products. Such investigations are interesting and provide insights into firms’ profitability, consumer surplus, and social welfare under competition between an OEM and an IR in a two-period dynamic model that considers the capacity and quality policies of the IR.

The remainder of this paper is organized as follows. Section 2 surveys the related literature while comparing these studies with our work. In Sect. 3, we develop the demands for firms from a consumer utility function incorporating prices and the average quality level. Then, we build the functions of the firms’ profits, consumer surplus, and social welfare. In Sect. 4, we derive the firms’ equilibrium decisions by dynamic programming and the conditions of the production-quality policies. Then, we discuss the choices of production-quality policies. In Sect. 5, we analytically characterize firms’ equilibrium decisions, profits, and consumer surplus. In Sect. 6, we perform numerical experiments to investigate parametric effects on the firms’ profits, the consumer surplus, and social welfare. The final section concludes the study with a brief summary and suggests potential future research directions.

2 Literature review

Many researchers have provided thorough literature reviews on remanufacturing in the fields of revenue management and management science (Ilgin and Gupta 2010; Souza 2012; Steeneck and Sarin 2013; Govindan et al. 2015; Wei et al. 2015; Kurilova-Palisaitiene et al. 2018). In this section, we position our work within the literature by providing an overview of the related streams of research, rather than an exhaustive review. In this paper, we study the production-quality decisions in a duopoly with remanufacturing under a two-period dynamic model. Two-period settings are commonly adopted in research on remanufacturing or closed-loop supply chains (CLSCs) (e.g., Majumder and Groenevelt 2001; Debo et al. 2005, 2006; Ferguson and Toktay 2006; Atasu et al. 2008; De Giovanni and Zaccour 2014; Chen et al. 2019). Majumder and Groenevelt (2001) examined pricing decisions in a duopolistic competition between an OEM and local IR under a two-period static model and investigated different configurations of reverse logistics for collecting used products. Debo et al. (2005) considered a monopolistic model under a two-period dynamic setting in which an OEM determines whether to sell remanufactured products and determines the level of remanufacturing associated with the return rate and product technology. Ferguson and Toktay (2006) also considered a two-period static model in which an OEM competes with a local IR and makes its recovery decisions to deter the entry of the IR. Atasu et al. (2008) incorporated the effects of product-life-cycle and different consumer types into both monopolistic and duopolistic models in a CLSC and proposed that a two-period static setting is sufficient for obtaining managerial insights while maintaining analytical tractability. De Giovanni and Zaccour (2014) discussed the collection strategy of an IR who determines whether to exclusively undertake the reverse logistic or outsource it to either a retailer or third-party collector under a two-period dynamic setting and compared the IR's performances between decentralized and centralized CLSCs. Moreover, De Giovanni and Zaccour (2014) proposed that the return rate captures the dynamic nature and is more appropriate for considering the dynamic setting in their two-period CLSC model. Chen et al. (2019) examined a two-period model in which a monopolistic firm sells a first-generation new product in the first period and guarantee money back for returned products; in the second period, the firm opts to sell only the second-generation new product, only the remanufactured product, or both. Then, they investigated static pricing and money-back decisions and discussed the optimal production strategy for the firm during the second period. Two-period settings are also used in CLSC research for other issues, such as technology licensing (Hong et al. 2017), operations in reverse logistics(Ferrer and Swaminathan 2006, 2010), strategic choices (De Giovanni et al. 2016; Mitra 2016), and product design (Wu 2012, 2013). In these studies, the two-period setting captures the essence of a finite lifetime for new products and the interactions between new and remanufactured products; specifically, a proportion of the new products are collected for remanufacturing in the end of the first period, and then the remanufactured products are sold in the second period in competition with new products. Moreover, the two-period setting reduces the model complexity, allowing for closed-form results without losing managerial insights (Majumder and Groenevelt 2001; Ferguson and Toktay 2006; Atasu et al. 2008). However, these studies overlook the relationship between production decisions and quality policies. This paper bridges this gap by associating an IR's production capacity with its quality policies and then investigates the IR's quality policies and the firms' production decisions in quality competition under a two-period dynamic setting.

Our study is also related to the operations management literature regarding remanufacturing capacities. The availability of EOL products is critical to the capacities of remanufacturers (Capraz et al. 2015; Global Industry Analysts, Inc. 2015) and thus affects IR decisions and interactions with OEMs. For example, Ferguson and Toktay (2006) found that an OEM can choose to collect EOL products to deter the entry of an IR such that the capacity and profitability of IRs are limited. Consequently, IRs are likely to be more aggressive when collecting EOL products in recycled markets. Therefore, analyses of firms' decisions (e.g., take-back incentives, acquisition decisions, and collection strategy) in recycled markets have attracted considerable attention in the field of remanufacturing (e.g., Heese et al. 2005; Liang et al. 2009; Teunter and Flapper 2011; Stindt and Sahamie 2012; Bulmuş et al. 2014; Mitra 2015; Wu 2015). Heese et al. (2005) considered that an OEM adopts a take-back strategy as a deterrent strategy to prevent IRs from selecting their profitable strategies. These researchers discussed OEMs' take-back behavior under different competitive environments. Teunter and Flapper (2011) examined the optimal acquisition and remanufacturing policies regarding the sorting problem of collected cores for remanufacturing between an IR and third-party collectors in a centralized system. Mitra (2015) discussed the sales and acquisition prices in a monopolistic CLSC in which consumers can be divided two segments: quality-conscious primary customers and price-sensitive secondary customers. The researchers considered a deterministic single-period setting and investigated whether a firm determines its sales price or the acquisition price at an economical level with respect to the parametric changes. Wu (2015) further extended previous works by considering a duopolistic supply chain in which both price competition in a sales market and incentive competition in a recycled market have emerged; then, Wu discussed the firms' sales and collection decisions and an IR's collection strategy in a deterministic model. In these works, the IRs aim to increase the availability of EOL products to increase their remanufacturing capacities such that remanufacturing economies of scales can be achieved. In this study, we further incorporate the interdependency between remanufacturing capacity and the quality policy chosen by the IR. Furthermore, we investigate the effect of the IR's quality policy on profits, consumer surplus, and social welfare.

Another growing stream in the field of revenue management related to this study considers quality issues in remanufacturing (e.g., Galbreth and Blackburn 2006, 2010; Teunter and Flapper 2011; Atasu and Souza 2013; Örsdemir et al. 2014; Radhi and Zhang 2015; Cui et al. 2017; Wu and Kao 2018). Diallo et al. (2016) provided a review regarding quality, reliability and maintenance issues in CLSCs with remanufacturing and indicated that the previous studies mainly focused on the design quality of new products or EOL products collected from markets. For example, Galbreth and Blackburn (2006) considered quality as an exogenous parameter affecting the acquisition and sorting policies of an IR; specifically, remanufacturing costs are lower when the average quality of take-back items is higher. Galbreth and Blackburn (2010) further formulated an IR's remanufacturing cost to be associated with the quality of take-back items and examined the economic lot size of an IR for remanufacturing. Teunter and Flapper (2011) considered multiple discrete quality classes with quality uncertainty under either deterministic or uncertain demand and performed numerical experiments to analyze the remanufacturing decisions regarding quality and demand uncertainty due to analytical intractability. Atasu and Souza (2013) regarded quality as an observable measure that increases a consumer's valuation for the product and compared a firm's quality choice among three different recovery forms under a monopolistic model. Atasu and Souza (2013) demonstrated that the firm will choose a higher-quality choice under a legislative take-back scenario than under a voluntary take-back scenario and that a higher-quality choice will be chosen under a higher recovery rate. However, in their model, quality choice and recovery activity were controlled by a monopolistic firm; thus, competition and remanufacturing capacity in CLSCs were not considered. Örsdemir et al. (2014) considered that an OEM competes with an IR for sales and that the OEM uses quality as a strategic lever when facing different levels of IR competition. They discovered that ignoring the OEM's quality choice leads one to overestimate the benefits from remanufacturing and that consumer surplus may decrease when the entry of IR remanufacturing is successful. Maiti and Giri (2015) formulated a CLSC in which a collector provides EOL items to an OEM who produces both new and remanufactured products and sells new products through a retailer. They explored both quality and price decisions under different supply chain models but disregarded competition between new and remanufactured products by assuming that they are indifferent to consumers; i.e., new and remanufactured products are sold at the same price and quality level. Cui et al. (2017) turned the attention of new product quality choice to remanufactured products regarding various consumer preferences in an integrated model and demonstrated that improving the quality level may be beneficial to the integrated system when the cost is not excessively high. However, these researchers focused on an integrated model and thus did not consider competition between firms. Recently, Wu and Kao (2018) studied coopetition in a CLSC in which an OEM and IR cooperate on quality improvement but compete for sales; moreover, they focused on analyzing the impact of cooperative mechanisms on equilibrium decisions, profits and consumer surplus. In these related studies, quality was considered as the attributes of new products or as OEM choices. However, to the best of our knowledge, few studies have considered the strategic quality choice of IRs in a competitive environment.

In this study, we examine an IR's quality selection as a competitive strategy affecting an OEM's production decisions. Moreover, the IR's quality strategy is associated with its remanufacturing capacity. Our study contributes to the literature by simultaneously considering the IR's quality choice and remanufacturing capacity. Our study is related to the work of Melumad and Ziv (2004), who considered a Cournot duopoly with a limited production capacity and considered reducing the quality level to enable firms to increase their production capacity. Melumad and Ziv (2004) found that reducing the quality level is likely to improve consumer surplus and that a higher mandated quality standard is never beneficial to social welfare. Nevertheless, they focused on a traditional supply chain under a static setting; thus, remanufacturing and the interaction between the forward and reverse chains were not discussed. This paper aims to fill the gap in the literature by examining the IR's quality choice and remanufacturing capacity while considering Cournot competition between the OEM and the IR in a two-period dynamic model. To highlight the contributions of this study, Table 1 summarizes the issues and model settings and compares them to those of the relevant research. This study brings the relationship between an IR's quality choice and its capacity into a two-period remanufacturing

Table 1 Brief summary of issues and settings considered in the literature

Author(s)	Issues			Planning	Decision	Competition	Model
(Year)	Quality	Capacity	Rmfg.	Horizon	Variable	Type	Type
This study	✓	✓	✓	Two-period	Quantity	Duopoly	Dynamic
Melumad and Ziv (2004)	✓[c]	✓		Single-period	Quantity	Duopoly	Static
Ferguson and Toktay (2006)		✓	✓	Two-period	Quantity	Monopoly	Static
Atasu et al. (2008)		✓	✓	Two-period	Price	Duopoly	Static
Galbreth and Blackburn (2010)	✓[a]		✓	Single-period	Quantity	N/A	Static
Örsdemir et al. (2014)	✓[c]	✓[b]	✓	Single-period	Quantity	Duopoly	Static
De Giovanni and Zaccour (2014)			✓	Two-period	Price	Monopoly	Dynamic
Mitra (2015)		✓	✓	Single-period	Price and acquistion	Monopoly	Static
Wu (2015)		✓	✓	Single-period	Price and incentive	Duopoly	Static
Cui et al. (2017)	✓[c]		✓	Single-period	Price	N/A	Static
Wu and Kao (2018)	✓[c]		✓	Multi-period	Price	Duopoly	Static and dynamic

Rmfg. remanufacturing

[a] Quality is exogenous

[b] Remanufacturing capacity is independent of quality level

[c] Quality is not chosen by the IR

problem and considers the dynamic interaction between the firms' quantity decisions across the two periods.

3 Model formulation

Consider a two-period supply chain model consisting of an OEM, denoted by o, and an IR, denoted by r. In the first period, the OEM sells new products in a monopoly. In the second period, the IR recovers EOL products that were sold by the OEM in the first period and sells them as remanufactured products. Because the new and remanufactured products are substitutable for consumers, the firms compete in a duopolistic Cournot game in the second period. In the market, consumers make purchasing choices depending on their utilities, which are associated with the firms' sales prices and average quality levels. We consider two possible quality levels for remanufactured products, namely, high (h) and low (l).[1] A high-quality remanufactured product requires more EOL products to obtain a qualified core and thus consumes more collected quantities for remanufacturing than low-quality remanufactured products. Because the IR's production is limited by the collection of EOL products, the IR may reduce the average quality level of remanufactured products to increase total production. Consistent with Melumad and Ziv (2004), we consider the quality levels of the low- and high-quality products to be 0 and 1, respectively. Thus, the average quality of remanufactured products can be designed as $\chi_r = q_{rh}/(q_{rl} + q_{rh})$, where $0 \leq \chi_r \leq 1$ and q_{rl} and q_{rh} represent the quantities of the low- and high-quality remanufactured products, respectively. This formulation indicates that consumers perceive the average quality of remanufactured products to be higher when the IR selects a larger amount of high-quality remanufactured products. Therefore, the IR can control the average quality of remanufactured products by allocating production quantities between low- and high-quality products.

The decision process is as follows. In the first period, the OEM determines the sales quantity q_1 based on its anticipation of the IR's quality choice; in the second period, the OEM determines the sales quantity q_o and the IR determines the sales quantities q_{rl} and q_{rh}. The IR has three quality policies, i.e., H, L, and C, indicating that it produces pure high-quality products (i.e., $q_{rl} = 0$ and $q_{rh} > 0$), pure low-quality products (i.e., $q_{rl} > 0$ and $q_{rh} = 0$), and both low- and high-quality products (i.e., $q_{rl} >$ and $q_{rh} > 0$), respectively. Moreover, because the IR collects EOL products for remanufacturing, two possible statuses exist for remanufacturing capacity. Specifically, status U indicates that the IR's remanufacturing capacity is ample and thus that the IR can choose a quantity at an economy of scale. However, status B indicates that the IR's remanufacturing capacity is limited, and thus, the IR's quantity

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[1] As stated by Melumad and Ziv (2004), an alternative approach is that a manufacturer selects its average quality level from a continuous bounded set, inevitably leading to model complexity. The two-level representation of quality selection enables us to simplify the explanation and derive the key insights analytically.

decision is contingent on the collected quantity. Throughout the paper, we use subscripts $i \in \{o, r\}$ to denote the firms.

3.1 Consumer utility and inverse demand functions

Consumers make their purchasing choices based on the utilities of both firms' products. To capture heterogeneity in consumer preferences, we assume that the consumer's reservation price, denoted by θ, is uniformly distributed between 0 and 1 (i.e., $f(\theta) \sim$ Uniform $[0, 1]$) (Atasu et al. 2008; Cattani et al. 2006; Ferguson and Toktay 2006; Wu 2012). In the first period, a type-θ consumer receives utility $U_1 = \theta - p_1 + \alpha\,\chi_o$ from the new product sold by the OEM, where p_1 denotes the sales price of the OEM in the first period, $0 \le \chi_o \le 1$ denotes the average quality level of new products, and α is a scaling factor for consumer sensitivity with respect to the average quality level (i.e., a higher value for α indicates that consumers are more sensitive to the average quality level). We can derive the new product demand in the first period, as follows: $q_1 = \int_{\theta \in \{\theta_1 : U_1 \ge 0\}} f(\theta)\,\mathrm{d}\ \theta = 1 - p_1 + \alpha\,\chi_o$; thus, the inverse demand function is obtained: $p_1 = 1 - q_1 + \alpha\,\chi_o$. In the second period, a consumer receives a utility $U_o = \theta - p_o + \alpha\,\chi_o$ from a new product and $U_r = \rho\,\theta - p_r + \alpha\,\chi_r$ from a remanufactured product, where $0 < \rho < 1$ represents the discount factor of the reservation price for the remanufactured products compared to the new products; i.e., as ρ approaches one, consumers have the same reservation price for the remanufactured and new products. The demands of the products can be calculated as follows:

$$q_o = \int_{\theta \in \{\theta_o : U_o \ge \max\{U_r, 0\}\}} f(\theta)\,\mathrm{d}\ \theta = \frac{-\alpha\chi_o + p_o - p_r + \rho + \alpha\chi_r - 1}{\rho - 1},$$

$$q_r = \int_{\theta \in \{\theta_r : U_r \ge \max\{U_o, 0\}\}} f(\theta)\,\mathrm{d}\ \theta = \frac{\alpha\rho\chi_o - \rho p_o + p_r - \alpha\chi_r}{(\rho - 1)\rho}.$$

The total market demand $q_o + q_r$ is not constant; instead, it is dependent on the IR's price and average quality level. Without loss of generality, the average quality level of new products is normalized to 1, i.e., $\chi_o = 1$. To focus on the duopolistic model, we consider that $\rho - (1 + \alpha - c)/(q_{rh} + q_{rl}) \le 0$ for $q_o \ge 0$, where c is the unit production cost for a new product. Note that the detailed derivation of the condition for the duopolistic model is summarized in the Appendix. This assumption of ρ indicates that the consumer reservation price for remanufactured products is not overly high, and the market therefore remains profitable to the OEM.

We then substitute the forms of χ_o and χ_r into the demand functions q_o and q_r, and after some arrangement, we obtain the inverse demand functions as follows: $p_o = 1 + \alpha - q_o - \rho\left(q_{rh} + q_{rl}\right)$ and $p_r = \rho\left(1 - \left(q_o + q_{rh}\right)\right) + \alpha\,q_{rh}/(q_{rh} + q_{rl}) - \rho q_{rl}$. Consumers cannot distinguish the quality levels of each remanufactured product before purchasing. Based on the example of the production allocation of A9 chips between TSMC and Samsung, although many complicated techniques were shared to distinguish chip manufacturers of the iPhone, most consumers are still unable to distinguish the differences. In such a case, consumers perceive the quality level of a product based on information regarding the average quality level via, e.g., word of mouth, consumer communities, and social media, rather than the actual quality level. Therefore, we consider that the market price paid to the IR depends on the average quality level. Adding up the utilities of the consumers who made purchases yields consumer surplus, denoted by *CS*, as follows:

$$\begin{aligned} CS \equiv & \int_{\theta \in \{\theta_1 : U_1 \geq 0\}} U_1 f(\theta)\,\mathrm{d}\ \theta + \int_{\theta \in \{\theta_o : U_o \geq \max\{U_r, 0\}\}} U_o f(\theta)\,\mathrm{d}\ \theta \\ & + \int_{\theta \in \{\theta_r : U_r \geq \max\{U_o, 0\}\}} U_r f(\theta)\,\mathrm{d}\ \theta \\ & = \frac{1}{2}\left(q_1^2 + 2\rho q_o\left(q_{rh} + q_{rl}\right) + q_o^2 + \rho\left(q_{rh} + q_{rl}\right)^2\right). \end{aligned} \tag{1}$$

CS in (1) reveals that the total production of remanufactured products $(q_{rh} + q_{rl})$ can increase consumer surplus; therefore, the IR's economical choice of reducing the average quality level for profit maximization is not necessarily harmful to consumers, particularly when the IR's capacity is constrained by the collection of EOL products. Moreover, when both firms increase their quantities, i.e., a fierce competition emerges, the consumer surplus increases. Hence, the firms' equilibrium decisions, the conditions of the IR's production strategies, and the parametric effects on the firms' profits, consumer surplus, and social welfare should be investigated.

3.2 Profit functions of the firms

We now formulate the firms' profit functions. In the first period, the OEM selects the sales quantity in a monopoly, and in the second period, the OEM and IR determine their sales quantities simultaneously. We formulate the OEM's problem as a two-period model. Through backward induction, we first solve the firms' problems in the second period. Specifically, the OEM's second-period objective is

$$\max_{q_o \geq 0} \ \ \pi_o = (p_o - c) q_o. \tag{2}$$

Regarding the IR's problem, the IR's total production is limited by the collection of the EOL products at the end of the first period. We assume that only a proportion of the EOL products, denoted by γ, can be collected at the beginning of the second period; i.e., the $\gamma\, q_1$ of the EOL products can be collected at the beginning of the second period; i.e., a $\gamma\, q_1$ high-quality unit requires more EOL products to obtain a qualified core. Thus, the consumption rate of a high-quality unit, denoted by κ, is greater than that of a low-quality unit (normalized to 1); i.e., $\kappa > 1$. Formally, the constraint of the remanufacturing capacity can be formulated as follows: $q_{rl} + \kappa\, q_{rh} \leq \gamma\, q_1$. The IR's objective is to maximize profit by selecting the quantities of the high- and low-quality products, subject to the remanufacturing capacity constraint, as follows:

$$\max_{q_{rh} \geq 0, q_{rl} \geq 0} \ \ \pi_r = (p_r - \delta\, c)\,(q_{rl} + q_{rh}) + \beta\, q_{rl} - F(q_{rl}) \tag{3}$$

$$\text{s.t.} \quad q_{rl} + \kappa\, q_{rh} \leq \gamma\, q_1, \quad q_{rl} \geq 0, \quad q_{rh} \geq 0. \tag{4}$$

The parameter $0 < \delta < 1$ represents the unit aggregate cost of a remanufactured product incurred in production and in collection as a fraction of the new product cost. A higher value of δ causes the unit cost of a remanufactured product to be closer to that of a new product, indicating a smaller cost saving from remanufacturing. When a larger amount of low-quality products is produced, the material cost savings will be higher but the expected incremental cost associated with, e.g., warranty costs, damage and faults, will also be higher. Hence, we denote β as the unit cost saving of a low-quality product and formulate the expected incremental cost as quadratic and convex in the amount of the low-quality products by considering $F(q_{rl}) \equiv (\tau \times q_{rl}^2)/2$. Quadratic forms are commonly adopted in the literature (e.g., Savaskan et al. 2004; Savaskan and Van Wassenhove 2006; Ha et al. 2011; Shang et al. 2016) to capture the increasing managerial cost associated with investment decisions. Specifically, when the number of low-quality products increases, the managerial incremental cost will increase, assuring the existence of the scale of economies in q_{rl}.

We use the superscript "*" to denote the firms' subgame-perfect Nash equilibrium (SPNE) decisions. Using dynamic programming, the OEM's problem in the first period is given by

$$\max_{q_1 \geq 0} \quad \varPi_o = \pi_1 + \pi_o^*, \tag{5}$$

where $\pi_1 = (p_1 - c)\, q_1$ and $\pi_o^* = \pi_o|_{q_o = q_o^*, q_{rh} = q_{rh}^*, q_{rl} = q_{rl}^*}$. Specifically, the recursive procedure follows a backward induction by solving the problem in the first period as a function of π_1 and π_o^* by including the firms' SPNEs in the second period. Social welfare is the sum of consumer surplus and the firms' profits:

$$SW = CS + \pi_1 + \pi_o + \pi_r. \tag{6}$$

4 Equilibrium decisions

We now derive the firms' equilibrium decisions. Throughout the paper, the proofs of the propositions are included in the electronic companion. We first solve the problems of the OEM and IR in the second period. The Lagrangian function of the IR's problem in (3) and (4) is written as

$$L_r = \pi_r + \lambda_k(\gamma\, q_1 - q_{rl} - \kappa\, q_{rh}) + \lambda_h\, q_{rh} + \lambda_l\, q_{rl}, \tag{7}$$

where λ_k, λ_h, and λ_l are nonnegative Lagrangian multipliers. Proposition 1 characterizes the concavity of the firms' profit functions with respect to the decisions, assuring the uniqueness of the equilibrium decisions.

Table 2 Summary of the scenarios and corresponding values of the Lagrangian multipliers

Remanufacturing capacity	IR's quality policies		
	$q_{rh} \geq 0, q_{rl} = 0$ (Policy *H*)	$q_{rh} = 0, q_{rl} \geq 0$ (Policy *L*)	$q_{rh} \geq 0, q_{rl} \geq 0$ (Policy *C*)
Remanufacturing capacity Is ample (status *U*)	$\lambda_k = 0, \lambda_h \geq 0, \lambda_l = 0$ (Scenario *HU*)	$\lambda_k = 0, \lambda_h = 0, \lambda_l \geq 0$ (Scenario *LU*)	$\lambda_k = 0, \lambda_h = 0, \lambda_l = 0$ (Scenario *CU*)
Remanufacturing capacity Is limited (Status *B*)	$\lambda_k \geq 0, \lambda_h \geq 0, \lambda_l = 0$ (Scenario *HB*)	$\lambda_k \geq 0, \lambda_h = 0, \lambda_l \geq 0$ (Scenario *LB*)	$\lambda_k \geq 0, \lambda_h = 0, \lambda_l = 0$ (Scenario *CB*)

Proposition 1 *L_r is jointly concave in q_{rl} and q_{rh}, and π_o is concave in q_o.*

According to the constraints of the IR's problem in (4), six possible scenarios combining three quality policies for the IR, i.e., *H*, *C*, and *L*, and two possible statuses for remanufacturing capacity exist, i.e., *U* and *B*. The corresponding notation and the values of the Lagrangian multipliers in (7) are summarized in Table 2. Similar to Atasu et al. (2008); Ferrer and Swaminathan (2006), and Wu (2012), we avoid trivial results by considering a sufficient condition $\rho - (2c\delta)/(1 - \alpha + c) \geq 0$, such that $q_{rh} \geq 0$ and $q_{rl} \geq 0$. This condition indicates that when the consumer reservation price for the remanufactured products is sufficiently high, entering the market is profitable for the IR, and thus the interaction between the OEM and IR emerges. In the following section, we discuss the firms' SPNE decisions based on the IR's production policies for clarity.

4.1 Policy *H*: the IR produces only high-quality products

Under policy *H*, the IR produces only high-quality products. Then, solving the Karush–Kuhn–Tucker (KKT) conditions yields the firms' SPNE quantities in the second period, as presented in Proposition 2.

Proposition 2 *Under policy H, only high-quality products are provided by the IR, and the firms' SPNE quantities are as follows:*

(i) *When*

$$\gamma \geq \gamma^H \equiv \frac{\kappa(\alpha(\rho - 2) + 2c\delta - (c + 1)\rho)}{(\rho - 4)\rho q_1} \quad \text{and} \quad \alpha \geq \alpha^{HU} \equiv \beta,$$

the IR will not produce low-quality products and the remanufacturing capacity is unbinding, denoted by scenario HU, and the SPNE quantities are

$$q_o^{HU} = \frac{\alpha + c(\delta - 2) - \rho + 2}{4 - \rho}, \quad q_{rh}^{HU} = \frac{\alpha(\rho - 2) + 2c\delta - (c+1)\rho}{(\rho - 4)\rho}, \quad \text{and}$$

$$q_{rl}^{HU} = 0.$$

(ii) *However, when*

$$\gamma < \gamma^H \quad \text{and}$$

$$\alpha \geq \alpha^{HB} \equiv \frac{\kappa(2\beta\kappa - 2c\delta(\kappa - 1) + (c+1)(\kappa - 1)\rho) + \gamma(\kappa - 1)(\rho - 4)\rho q_1}{\kappa((\kappa - 1)\rho + 2)},$$

the IR's remanufacturing capacity is binding, denoted by scenario HB, and the SPNE quantities are

$$q_o^{HB} = \frac{\alpha\kappa - c\kappa + \kappa - \gamma\rho q_1}{2\kappa}, \quad q_{rh}^{HB} = \frac{\gamma q_1}{\kappa}, \quad \text{and} \quad q_{rl}^{HB} = 0.$$

In Proposition 2, only high-quality products are selected by the IR when the consumers are sensitive to the quality level (α is greater). However, the reverse is true when the cost savings of the low-quality products are more significant because $\partial\alpha^{HB}/\partial\beta > 0$. The OEM observes the return rate and consumer quality sensitivity to determine its first-period decision; i.e., the OEM believes that the IR produces only high-quality products with an ample capacity whenever $\alpha \geq \alpha^{HU}$ and $\gamma \geq \gamma^H$. As a result, we incorporate the firms' second-period SPNE decisions in Proposition 2 into the OEM's first-period problem in (5) and then solve for the OEM's first-period quantity, as summarized in Corollary 1.

Corollary 1 *(i) When* $\gamma \geq \gamma^H$ *and* $\alpha \geq \alpha^{HU} \equiv \beta$, $q_1^{HU} = (1 + \alpha - c)/2$. *(ii) However, when* $\gamma < \gamma^H$ *and* $\alpha \geq \alpha^{HB}$, $q_1^{HB} = [\kappa(1 + \alpha - c)]/(\gamma\rho + 2\kappa)$.

From Corollary 1, $q_1^{HU} - q_1^{HB} = [\gamma\rho(1 + \alpha - c)]/(2\gamma\rho + 4\kappa) > 0$, indicating that the OEM chooses the smaller sales quantity in the first period when the IR's remanufacturing capacity is limited by the collected quantity over that when the IR has ample remanufacturing capacity. This implies that when the IR's sales quantity is contingent on the OEM's sales quantity in the first period, the OEM would like to reduce the IR quantity to obtain a higher sales margins by decreasing its sales quantity in the first period.

By incorporating the OEM's equilibrium quantity in the first period, as detailed in Corollary 1, into the firms' SPNE quantities and after some arrangement, we can obtain the firms' equilibrium decisions designated by q_o^{k*} and $q_{rh}^{k\,*}$, where $k \in \{HU, HB\}$.

4.2 Policy *L*: the IR produces only low-quality products

Under policy L, the IR produces only low-quality products. The firms' SPNE quantities are summarized in Proposition 3.

Proposition 3 *In policy L, only low-quality products are provided by the IR, and the firms' SPNE quantities are as follows:*

(i) *When*

$$\gamma \geq \gamma^L \equiv \frac{-2\beta + \rho(\alpha - c - 1) + 2c\delta}{q_1((\rho - 4)\rho - 2\tau)} \quad \text{and}$$
$$\alpha \leq \alpha^{LU} \equiv \frac{\beta(\rho - 4)\rho + \tau(c(\rho - 2\delta) + \rho)}{\rho(\rho + \tau - 4) - 2\tau},$$

the IR will not produce high-quality products, and the remanufacturing capacity is unbinding, denoted by scenario LU. The SPNE quantities are

$$q_o^{LU} = \frac{\rho(-2\alpha + \beta - c(\delta - 2) + \rho - 2) + \tau(-\alpha + c - 1)}{(\rho - 4)\rho - 2\tau}, \quad q_{rh}^{LU} = 0, \quad \text{and}$$
$$q_{rl}^{LU} = \frac{-2\beta + \rho(\alpha - c - 1) + 2c\delta}{(\rho - 4)\rho - 2\tau}.$$

(ii) *However, when*

$$\gamma < \gamma^L \quad \text{and}$$
$$\alpha \leq \alpha^{LB} \equiv \frac{2\beta\kappa - 2c\delta(\kappa - 1) + (c + 1)(\kappa - 1)\rho + \gamma q_1((\kappa - 1)(\rho - 4)\rho - 2\kappa\tau)}{(\kappa - 1)\rho + 2},$$

the IR's remanufacturing capacity is binding, denoted by scenario LB, and the SPNE quantities are

$$q_o^{LB} = \frac{1}{2}\left(1 + \alpha - c - \gamma\rho q_1\right), \quad q_{rh}^{LB} = 0, \quad \text{and} \quad q_{rl}^{LB} = \gamma\, q_1.$$

From Proposition 3, when the consumer sensitivity to the quality level, i.e., α, is lower than the threshold α^{LU} (α^{LB}), only production of low-quality products is economical to the IR under an ample (limited) remanufacturing capacity. Because $\partial\,\alpha^{LU}/\partial\,\beta > 0$ and $\partial\,\alpha^{LB}/\partial\,\beta > 0$, the cost savings from reducing quality encourage the IR to produce only low-quality products. The equilibrium quantity of the OEM in the first-period can be obtained based on the SPNE decisions in Proposition 3, as summarized in Corollary 2.

Corollary 2 *(i) When* $\gamma \geq \gamma^L$ *and* $\alpha \leq \alpha^{LU}$, $q_1^{LU} = (1+\alpha-c)/2$. *(ii) However, when* $\gamma < \gamma^L$ *and* $\alpha \leq \alpha^{LB}$, $q_1^{LB} = (1+\alpha-c)/(\gamma\rho+2)$.

Similar to the finding of Corollary 1, Corollary 2 reveals that $q_1^{LU} > q_1^{LB}$. Under policy *L*, the OEM behaves similarly; i.e., the OEM will preserve higher sales margins by decreasing its first-period production to lower the IR sales quantity limited by the collected quantity.

4.3 Policy *C*: the IR produces both high- and low-quality products

We now consider policy *C*, under which the IR produces both high- and low-quality products. Proposition 4 presents the firms' SPNE decisions.

Proposition 4 *Under policy C, the IR produces both high- and low-quality products, and the firms' SPNE quantities are as follows:*

(i) *When*

$$\gamma \geq \gamma^C \equiv \frac{1}{q_1}\left(\frac{(\kappa-1)(\alpha-\beta)}{\tau} + \frac{\kappa(\alpha(\rho-2)+2c\delta-(c+1)\rho)}{(\rho-4)\rho}\right) \quad \text{and}$$

$$\alpha^{LU} < \alpha < \beta,$$

the IR will produce high- and low-quality products, and the remanufacturing capacity is unbinding, denoted by scenario CU. The SPNE quantities are

$$q_o^{CU} = \frac{\alpha + c(\delta-2)-\rho+2}{4-\rho}, \quad q_{rh}^{CU} = \frac{\alpha-\beta}{\tau} + \frac{\alpha(\rho-2)+2c\delta-(c+1)\rho}{(\rho-4)\rho}, \quad \text{and}$$

$$q_{rl}^{CU} = \frac{\beta-\alpha}{\tau}.$$

(ii) *However, when* $\gamma < \gamma^C$ *and* $\alpha^{LB} < \alpha < \alpha^{HB}$, *the IR's remanufacturing capacity is binding, denoted by scenario CB. The SPNE quantities are*

$$q_o^{CB} = \frac{\rho(-\bar{\kappa})(-c(\delta-2)(-\bar{\kappa})-2\alpha\kappa+\alpha+\kappa(\beta+\rho-2)-\rho+2)+\kappa^2\tau(-\alpha+c-1)+\gamma\kappa\rho q_1\tau}{(\rho-4)\rho(-\bar{\kappa})^2-2\kappa^2\tau},$$

$$q_{rh}^{CB} = \frac{\gamma q_1((\rho-4)\rho(-\bar{\kappa})-2\kappa\tau)-\Omega}{(\rho-4)\rho(-\bar{\kappa})^2-2\kappa^2\tau}, \quad \text{and} \quad q_{rl}^{CB} = \frac{\kappa\,\Omega-\gamma(\rho-4)\rho q_1(-\bar{\kappa})}{(\rho-4)\rho(-\bar{\kappa})^2-2\kappa^2\tau},$$

where $\bar{\kappa} \equiv= 1-\kappa$ and $\Omega \equiv 2(c\delta(-\bar{\kappa})+\alpha-\beta\kappa)+\rho(-\bar{\kappa})(\alpha-c-1)$.

In Proposition 4, α^{HB}, α^{LU}, and α^{LB} have been defined in Propositions 2 and 3, respectively. When α falls in a certain range, the OEM regards the production of both high- and low-quality products as being chosen by the IR; otherwise, the IR will choose to produce either high- or low-quality products. Thus, scenario *CU* (scenario *CB*) is exclusive to scenarios *HU* and *LU* (scenarios *HB* and *LB*). According to

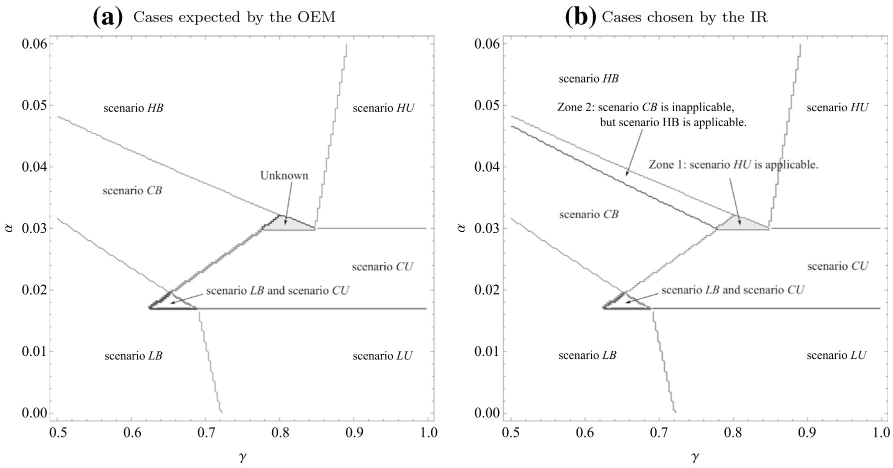


Fig. 1 Cases anticipated by the OEM and the available scenarios for the IR with respect to consumer quality sensitivity α and the return rate γ ($c = 0.1$, $\beta = 0.03$, $\delta = 0.75$, $\rho = 0.6$, $\tau = 0.05$ and $\kappa = 1.2$)

Proposition 4, the OEM's equilibrium quantity in the first period can be derived, as summarized in Corollary 3.

Corollary 3 *(i) When* $\gamma \geq \gamma^C$ *and* $\alpha^{LU} < \alpha < \alpha^{HU}$, $q_1^{CU} = (1 + \alpha - c)/2$. *(ii) However, when* $\gamma < \gamma^C$ *and* $\alpha^{LB} < \alpha < \alpha^{HB}$,

$$q_1^{CB} = \frac{1}{4}\left(2 + 2\alpha - 2c - \frac{2\gamma\kappa\rho\tau(1 + \alpha - c) + \bar{\kappa}\rho\Omega}{\kappa\tau(\gamma\rho + 2\kappa) - (\rho - 4)\rho\bar{\kappa}^2} + \frac{\bar{\kappa}\rho\Omega}{\kappa\tau(2\kappa - \gamma\rho) - (\rho - 4)\rho\bar{\kappa}^2}\right).$$

Substituting the equilibrium decisions in Corollary 3 into the firms' SPNE decisions in Proposition 4 yields the firms' equilibrium decisions, which are marked with a superscript "*".

4.4 Quality policy anticipated by the OEM and available to the IR

The previous derivations demonstrate the conditions of the scenarios. Notably, the OEM's anticipated scenario depends on the conditions of γ and α in Propositions 2-4, and its anticipation will determine its decisions of the first period. Subsequently, the IR's choice of the quality policy may be inconsistent with the OEM's anticipation. Thus, in this section, we further discuss the anticipated scenarios and the quality policy available to the IR with respect to the return rate, γ, and the consumer sensitivity to quality, α, as shown in Fig. 1a, b.

Table 3 Cases and corresponding conditions

Status of remanufacturing	IR's production policy		
	L	C	H
U	Scenario LU	Scenario CU	Scenario HU
	$\alpha \leq \alpha^{LU}$ and $\gamma \geq \gamma^{L}$	$\alpha^{LU} < \alpha < \alpha^{HU}$ and $\gamma \geq \gamma^{C}$	$\alpha \geq \alpha < \alpha^{HU}$ and $\gamma \geq \gamma^{H}$
B	Scenario LB	Scenario CB	Scenario HB
	$\alpha \leq \alpha^{LB}$ and $\gamma < \gamma^{L}$	$\alpha^{LB} < \alpha < \alpha^{HB}$ and $\gamma < \gamma^{C}$	$\alpha \geq \alpha^{HB}$ and $\gamma < \gamma^{H}$

We can see that the OEM's anticipated scenarios with respect to γ and α shown in Fig. 1a differ from the scenarios available to the IR, i.e., zones 1 and 2, shown in Fig. 1b. Specifically, in zone 1, which is formed by the conditions $\alpha^{HU} < \alpha < \hat{\alpha}^{HB}$, where $\hat{\alpha}^{HB} \equiv \alpha^{HB}|_{q_1=q_1^{HB*}}$, and $\gamma > \gamma^{C}$, no scenario meets the conditions, and thus, the scenarios are unknown to the OEM. For this unknown zone, because $\alpha > \alpha^{HU}$ and $\alpha < \alpha^{HB}$, we know that scenario HB violates the condition of α^{HB}, whereas scenario HU is a possible scenario. Thus, if the IR chooses scenario HU in the second period, the equilibrium decisions obtained in the second period satisfy the conditions, and thus scenario HU is applicable, as presented in Fig. 1b.

Regarding zone 2 in Fig. 1b, the OEM originally anticipates scenario CB being chosen by the IR; however, the equilibrium decisions of scenario CB are inapplicable, whereas those of scenario HB are applicable to the conditions. This result occurs because the OEM anticipates scenario CB being chosen by the IR when $\alpha < \hat{\alpha}^{HB}$. However, because $\hat{\alpha}^{HB} > \bar{\alpha}^{HB} \equiv \alpha^{HB}|_{q_1=q_1^{CB*}}$, the equilibrium decisions of scenario CB within the region of $\bar{\alpha}^{HB} < \alpha < \hat{\alpha}^{HB}$ do not meet the conditions, and the IR therefore chooses scenario HB at equilibrium when $\alpha > \bar{\alpha}^{HB}$. In addition, based on the numerical experiments, this situation does not occur when the IR chooses policy L; i.e., $\hat{\alpha}^{LB} > \alpha^{LB}|_{q_1=q_1^{CB*}}$, where $\hat{\alpha}^{LB} \equiv \alpha^{LB}|_{q_1=q_1^{LB*}}$. This result indicates that the OEM's anticipated scenarios are identical to the IR's chosen scenarios when only low-quality products are provided by the IR. Based on this analysis, we summarize the findings regarding the scenarios in Remark 1.

Remark 1 The findings regarding the OEM's anticipated scenarios and the scenarios available to the IR are summarized, as follows:

(i) Under ample remanufacturing capacity, the OEM's anticipated scenarios are identical to the IR's choices of scenarios.

(ii) Under limited remanufacturing capacity, the OEM anticipates that scenario HB holds when $\alpha \geq \hat{\alpha}^{HB}$, scenario CB holds when $\hat{\alpha}^{LB} < \alpha < \hat{\alpha}^{HB}$, and scenario LB holds when $\alpha \leq \hat{\alpha}^{LB}$.

(iii) Under limited remanufacturing capacity, the IR chooses scenario HB when $\alpha \geq \bar{\alpha}^{HB}$, scenario CB when $\hat{\alpha}^{LB} < \alpha < \bar{\alpha}^{HB}$ and scenario LB holds when $\alpha \leq \hat{\alpha}^{LB}$.

(iv) When $\alpha^{HU} < \alpha < \hat{\alpha}^{HB}$ and $\gamma > \gamma^C$, no scenario meets the OEM's condition, but the IR will choose scenario *HU*.
(v) When $\alpha^{CU} < \alpha < \hat{\alpha}^{LB}$ and $\gamma > \gamma^C$, both scenarios *LB* and *CB* are available to the OEM and the IR.

5 Analysis

In this section, we characterize the firms' equilibrium decisions, profits and consumer surplus; then, we analyze the IR's quality choices by investigating the conditions of α. Table 3 summarizes the conditions of the scenarios, as shown in Corollaries 1, 2, and 3. According to the conditions of α, scenarios *HU*, *LU*, and *CU* (scenarios *HB*, *LB*, and *CB*) are exclusive; therefore, only one scenario will hold. Moreover, under any scenario, there is only one possible remanufacturing capacity status depending on the condition of γ.

5.1 Analysis of the equilibrium decisions

We first discuss the parametric effects on the firms' equilibrium decisions and the status of the IR's remanufacturing capacity under quality policy *H*, as shown in Proposition 5.

Proposition 5 *The parametric effects on the firms' equilibrium quantities are as follows: In scenario HU,*

(i) $\partial q_1^{HU*}/\partial \delta = 0, \partial q_o^{HU*}/\partial \delta > 0, \partial q_{rh}^{HU*}/\partial \delta < 0;$
(ii) $\partial q_1^{HU*}/\partial \kappa = \partial q_o^{HU*}/\partial \kappa = \partial q_{rh}^{HU*}/\partial \kappa = 0;$ *and*
(iii) $\partial q_1^{HU*}/\partial \alpha > 0, \partial q_o^{HU*}/\partial \alpha > 0, \partial q_{rh}^{HU*}/\partial \alpha > 0.$

In scenario HB,

(iv) $\partial q_1^{HB*}/\partial \delta = \partial q_o^{HB*}/\partial \delta = \partial q_{rh}^{HB*}/\partial \delta = 0;$
(v) $\partial q_1^{HB*}/\partial \kappa > 0, \partial q_o^{HB*}/\partial \kappa > 0, \partial q_{rh}^{HB*}/\partial \kappa < 0;$
(vi) $\partial q_1^{HB*}/\partial \alpha > 0, \partial q_o^{HB*}/\partial \alpha > 0, \partial q_{rh}^{HB*}/\partial \alpha > 0;$ *and*
(vii) $\partial q_1^{HB*}/\partial \gamma < 0, \partial q_o^{HB*}/\partial \gamma < 0, \partial q_{rh}^{HB*}/\partial \gamma > 0.$

The parametric effects on γ^H *are*

(viii) $\partial \gamma^H/\partial \delta < 0, \partial \gamma^H/\partial \kappa > 0,$ *and* $\partial \gamma^H/\partial \alpha > 0.$

From Proposition 5 (i)-(viii), we obtain the following findings: (1) When the cost of a remanufactured product, i.e., δ, increases, the remanufactured products are less competitive because of the decreased cost savings, causing the equilibrium quantity of the remanufactured products to decrease and that of the new products to increase. However, this result does not hold when the remanufacturing is constrained by the collected quantity because the IR quantity is selected at the level contingent on the collected quantity rather than economies of scale. (2) When the capacity of remanufacturing is sufficient, the material consumption rate of the high-quality product, i.e., κ, has no effect on the firms' equilibrium quantities. In contrast, when the capacity of remanufacturing is limited, an increase in κ will decrease IR production and lead the OEM to capture a greater market share by increasing its production in the first and second periods. (3) Regardless of whether remanufacturing capacity is limited or not, the consumer sensitivity to quality level, α, stimulates the IR to increase the quantity of high-quality products and then mitigate quantity competition, inducing the OEM to increase the equilibrium quantities. (4) When the remanufacturing capacity is unlimited, the return rate (γ) has no impact on the firms' equilibrium quantities; however, when the remanufacturing capacity is limited, a higher return rate will increase the IR's capacity and thus stimulates the IR to increase the quantity. This outcome causes the OEM to decrease its quantities to avoid fiercer competition.

(5) Proposition 5 (viii) shows that when the unit cost saving of the remanufactured products is less, i.e., δ is greater, their sales quantity decreases, and then the remanufacturing capacity is less likely to be constrained by the collected quantity. When a high-quality remanufactured product requires more material, the IR remanufacturing in policy H is more likely to be limited by the collected quantity. Moreover, when consumers are more sensitive to the quality (α increases), the intensity of competition is mitigated. In most scenarios, q_{rh} increases at a faster rate than q_1; thus, IR remanufacturing tends to be limited by the collected quantity.

Next, we discuss the firms' equilibrium decisions when policy L is adopted by the IR, and then, we characterize these equilibrium decisions in Proposition 6.

Proposition 6 *The parametric effects on the firms' equilibrium quantities are as follows: In scenario LU,*

(i) $\partial q_1^{LU*}/\partial \delta = 0, \partial q_o^{LU*}/\partial \delta > 0, \partial q_{rl}^{LU*}/\partial \delta < 0$;
(ii) $\partial q_1^{LU*}/\partial \beta = 0, \partial q_o^{LU*}/\partial \beta < 0, \partial q_{rl}^{LU*}/\partial \beta > 0$; *and*
(iii) $\partial q_1^{LU*}/\partial \alpha > 0, \partial q_o^{LU*}/\partial \alpha > 0, \partial q_{rl}^{LU*}/\partial \alpha < 0$.

In scenario LB,

(iv) $\partial q_1^{LB*}/\partial \delta = \partial q_o^{LB*}/\partial \delta = \partial q_{rl}^{LB*}/\partial \delta = 0$;
(v) $\partial q_1^{LB*}/\partial \beta = \partial q_o^{LB*}/\partial \beta = \partial q_{rl}^{LB*}/\partial \beta = 0$;
(vi) $\partial q_1^{LB*}/\partial \alpha > 0, \partial q_o^{LB*}/\partial \alpha > 0, \partial q_{rl}^{LB*}/\partial \alpha > 0$; *and*
(vii) $\partial q_1^{LB*}/\partial \gamma < 0, \partial q_o^{LB*}/\partial \gamma < 0, \partial q_{rh}^{LB*}/\partial \gamma > 0$.

The parametric effects on γ^L *are*

(viii) $\partial \gamma^L / \partial \delta < 0, \partial \gamma^L / \partial \beta > 0,$ *and* $\partial \gamma^L / \partial \alpha < 0.$

The findings of Proposition 6 are summarized in the following. (1) In policy L, the effect of the cost savings (δ) and return rate (γ) on the firms' equilibrium quantities is similar to that in policy H. When the remanufacturing capacity is ample, the effect of β is opposite that of δ; i.e., when the cost savings from the low-quality products are greater, the cost advantage of the IR is more significant, inducing it to increase the equilibrium quantity and inducing the OEM to decrease its equilibrium quantity. (2) Under an unlimited remanufacturing capacity, both the OEM and the IR decide their quantities at the scales of economies in the second period. Thus, a higher consumer sensitivity to quality is advantageous to the sales of new products but harmful to the sales of low-quality remanufactured products. However, under limited remanufacturing capacity, the IR's quantity is contingent on the quantity of the EOL products rather than on the economical quantity. Because the OEM increases the quantity in α in the first period, a greater quantity of EOL products can be obtained during the second period, and thus, the IR can increase its quantities of high- and low-quality products. (3) The status of remanufacturing depends on the IR equilibrium behavior in production. Hence, when the IR decreases (increases) the quantity in δ and α (β), the remanufacturing capacity is less (more) likely to be constrained by the collected quantity of EOL products.

Finally, we characterize the equilibrium decisions in scenario *CU* in Proposition 7. Because of its complexity, an analytical analysis of the firms' equilibrium decisions in scenario *CB* is difficult to obtain.

Proposition 7 *The parametric effects on the firms' equilibrium quantities in scenario CU are as follows*:

(i) $\partial q_1^{CU^*} / \partial \delta = 0, \partial q_o^{CU^*} / \partial \delta > 0, \partial q_{rh}^{CU^*} / \partial \delta < 0, \partial q_{rl}^{CU^*} / \partial \delta = 0;$

(ii) $\partial q_1^{CU^*} / \partial \beta = 0, \partial q_o^{CU^*} / \partial \beta = 0, \partial q_{rh}^{CU^*} / \partial \beta < 0, \partial q_{rl}^{CU^*} / \partial \beta > 0;$ *and*

(iii) $\partial q_1^{CU^*} / \partial \alpha > 0, \partial q_o^{CU^*} / \partial \alpha > 0, \partial q_{rh}^{CU^*} / \partial \alpha > 0, \partial q_{rl}^{CU^*} / \partial \alpha < 0.$

Proposition 7 shows that when both high- and low-quality products are produced by the IR with an ample remanufacturing capacity, the parametric effects on the firms' equilibrium decisions may change. Specifically, (1) when the IR decisions are chosen at economic levels, the smaller cost savings of the remanufactured products (i.e., a greater value of δ) lead it to decrease the equilibrium quantity of the high-quality products; however, the IR's low-quality quantity is independent of δ. This result indicates that $q_{rl}^{CU^*}$ is chosen at its optimal economy of scale, regardless of quantity competition, whereas $q_{rh}^{CU^*}$ is treated by the IR as a means of competitive action to interact with the OEM. Moreover, (2) because the quantity of low-quality products is not a means of competition for the IR, the OEM's equilibrium quantity is independent of the cost savings from the IR's low-quality products, β. Intuitively, the IR will allocate more production to low-quality products when β increases. (3)

The effects of consumer quality sensitivity, α, in policy C is identical to those in scenarios H and L: an increase in α will cause the equilibrium quantities at the high-quality level to increase but will cause those at the low-quality level to decrease.

5.2 Analysis of the equilibrium profits

In this section, we analyze the effects of the parameters on the firms' equilibrium profits; however, because the analysis in scenario *CB* is intractable, we omit that analysis here and discuss it in the section regarding the numerical experiments.

Proposition 8 *When the IR remanufacturing capacity is ample,*

(i) $\partial \Pi_o^{j^*}/\partial \alpha > 0,\ j \in \{HU, LU, CU\};\ \partial \pi_r^{j^*}/\partial \alpha > 0,\ j \in \{HU, CU\},$ *and* $\partial \pi_r^{LU^*}/\partial \alpha < 0.$

However, when the IR remanufacturing capacity is constrained by the collected quantity,

(ii) $\partial \Pi_o^{j^*}/\partial \alpha > 0, j \in \{HB, LB\}; \partial \pi_r^{HB^*}/\partial \alpha > 0$ *and* $\partial \pi_r^{LB^*}/\partial \alpha > 0;$

(iii) $\partial \Pi_o^{j^*}/\partial \gamma < 0, \partial \pi_r^{j^*}/\partial \gamma > 0,$ *where* $j \in \{HB, LB\}.$

Proposition 8 indicates that regardless of the status of the IR capacity, a higher consumer sensitivity to the quality level is beneficial to the OEM and IR producing high-quality products in equilibrium. This trend occurs because when the consumers are more sensitive to the quality level, the intensity of the competition is mitigated for the firms to preserve the greater sales margins. However, when the IR chooses not to provide high-quality products, the increase in the consumer sensitivity to the quality level is harmful because the remanufactured product is less competitive. Regarding the return rate, when the IR capacity is limited, a higher return rate is advantageous to achieve the economies of scale and thus intensifies competition; therefore, the higher return rate is beneficial to the IR but harmful to the OEM. As a result, a greater amount of EOL products for remanufacturing is important for the IR to improve its competitiveness and thus is more profitable for the IR; however, the OEM would like to contain the IR's competitiveness by reducing the availability of EOL products.

Proposition 9 *When the IR remanufacturing capacity is ample,*

(i) $\partial \Pi_o^{j^*}/\partial \delta > 0, \partial \pi_r^{j^*}/\partial \delta < 0, j \in \{HU, LU, CU\};$

(ii) $\partial \Pi_o^{LU^*}/\partial \beta < 0, \partial \pi_r^{LU^*}/\partial \beta > 0;$

(iii) $\partial \Pi_o^{CU^*}/\partial \beta = 0, \partial \pi_r^{CU^*}/\partial \beta > 0.$

However, when the IR remanufacturing capacity is constrained by the collected quantity,

(iv) $\partial \Pi_o^{j^*}/\partial \delta = 0, \partial \pi_r^{j^*}/\partial \delta < 0, j \in \{HB, LB\}$;
(v) $\partial \Pi_o^{LB^*}/\partial \beta = 0, \partial \pi_r^{LB^*}/\partial \beta > 0$;

We characterize the firms' equilibrium profits regarding the cost-related parameters in Proposition 9. The firms' equilibrium profits under policy H are independent of β. Greater values of the IR's cost savings from remanufacturing or from reducing quality improve IR competitiveness and are thus beneficial to the IR but harmful to the OEM. However, when the IR remanufacturing capacity is constrained, the cost savings from remanufacturing or reducing quality are independent of quantity decisions and thus have no impact on OEM profit. This result suggests that an IR that possesses a low-cost advantage should develop sufficient remanufacturing capacity such that its low-cost advantage will effectively improve its competitiveness.

Proposition 10

(i) *The OEM equilibrium profit during the first period is always greater than that during the second period, i.e.,* $\pi_1^{j^*} > \pi_o^{j^*}$, $j \in \{HU, LU, CU, HB, LB\}$.
(ii) *In each scenario, the OEM equilibrium profit during the first period under ample remanufacturing capacity is always greater than that under limited remanufacturing capacity, i.e.,* $\pi_1^{j^*} > \pi_1^{j'^*}$, $j \in \{HU, LU\}$ *and* $j' \in \{HB, LB\}$.

We analyze the OEM's equilibrium profits during the first period in Proposition 10. Proposition 10 (i) reveals that in the first period, the IR has not yet entered the market; thus, the OEM would like to preserve a higher profit in response to the subsequent competition with the IR during the second period. Moreover, Proposition 10 (ii) shows that the status of the IR remanufacturing capacity will affect OEM behavior in the first period. When the IR remanufacturing capacity is ample, the OEM will face a more severe competition during the second period, inducing it to preserve more profit in the first period.

5.3 Analysis of consumer surplus

Proposition 11 *The parametric effects on consumer surplus are as follows:*

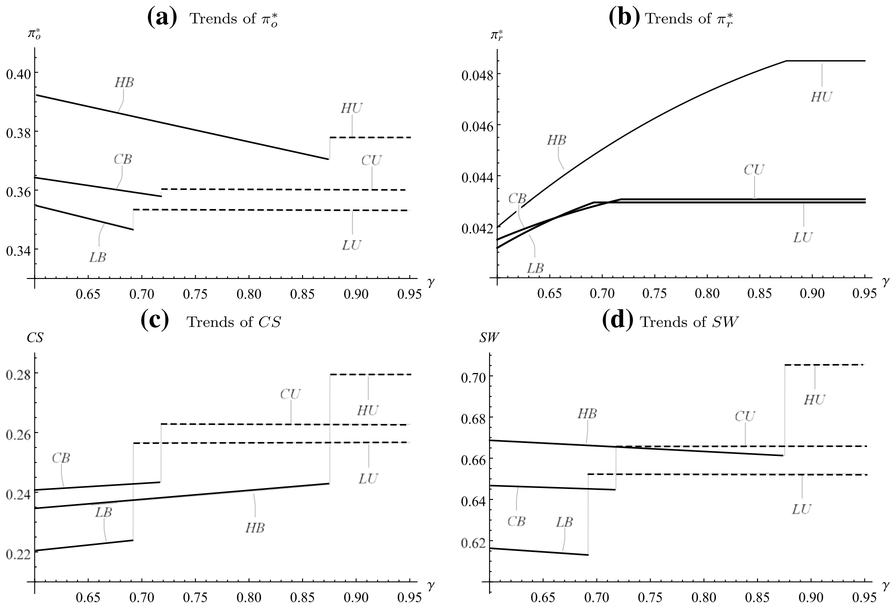
(i) $\partial CS^{j^*}/\partial \alpha > 0, j \in \{HU, LU, CU, HB, LB\}$.
(ii) $\partial CS^{j'^*}/\partial \gamma > 0, j' \in \{HB, LB\}$; *however,* $\partial CS^{j^*}/\partial \gamma = 0, j \in \{HU, LU, CU\}$.
(iii) $\partial CS^{j^*}/\partial \delta < 0$, $j \in \{HU, LU, CU, CB\}$; *however,* $\partial CS^{j'^*}/\partial \delta = 0$, $j \in \{HB, LB\}$.

(iv) $\partial CS^{LU^*}/\partial\beta > 0$ *and* $\partial CS^{CB^*}/\partial\beta > 0$; *however*, $\partial CS^{j^*}/\partial\beta = 0$, $j \in \{HU, CU, HB, LB\}$.

In this section, we analyze consumer surplus in Proposition 11 and omit the analysis of α and γ in scenario *CB* because of the analytical intractability. We obtain the following results: (1) When consumers are more sensitive to the quality level (α), consumer surplus will increase in all scenarios. This result indicates that when α increases, the increase in consumer utility caused by the increase of the perceived quality level exceeds the decrease in consumer utility caused by the price increase. Thus, decreasing the intensity of competition by raising the quality level of remanufactured products can increase consumer surplus. Moreover, because both the firms' profits increase in α, a higher level of consumer sensitivity to quality will increase social welfare. (2) When the IR remanufacturing capacity is limited, a higher return rate (γ) is beneficial to consumer surplus because an increasing quantity of remanufactured products reduces prices. Therefore, when the IR remanufacturing capacity is limited, the increase in IR capacity is beneficial to consumers.

(3) When the IR remanufacturing capacity is ample, the decrease in cost savings from remanufacturing (larger δ) decreases the IR's competitiveness. Accordingly, the IR will decrease its quantity, and the OEM will react in the opposite manner, as shown in Propositions 5, 6, and 7. The impact of δ on the IR's decisions is direct, but that on the OEM's decision is indirect, and thus, the negative effect on *CS* in (1) caused by the decrease in $q_{rh} + q_{rl}$ exceeds the positive effect caused by the increase in q_o, causing the consumer surplus to decrease with δ. However, when the IR remanufacturing capacity is limited, the IR competitiveness is restrained, and thus the cost savings from remanufacturing have no impact on firms' decisions, as shown in Propositions 5 and 6. Consequently, consumer surplus is not affected by δ in scenarios *LB* and *HB*, but it is affected in scenario *CB*. This result implies that when new products are more competitive, a limited remanufacturing capacity can mitigate the intensity of competition and thus may avoid the negative effects on the consumer surplus and social welfare. In scenario *CB*, the decreased cost savings from remanufacturing (δ) will induce the IR to produce a greater proportion of high-quality products, leading to a lower amount of remanufactured products, thus hurting the consumer surplus. (4) The IR cost savings from reducing the quality level (β) have no effect on consumer surplus, except when the IR produces only low-quality products with an ample capacity (i.e., scenario *LU*) or adopts mixed production with a limited capacity (i.e., scenario *CB*). Notably, under scenario *LB*, although the IR produces only low-quality products, its production quantity is chosen to be the amount of EOL products rather than the economical quantity, resulting in β having no effect on consumer surplus. Moreover, in scenarios *LU* and *CB*, a greater value of β will stimulate the IR to increase total production and decrease prices, thus benefiting consumer surplus. However, this effect vanishes when the IR with ample capacity provides both high- and low-quality products. As a result, when the IR cost savings from reducing the quality level are significant, the reduction in the expected consumer quality level by providing only low-quality products may benefit both the IR and consumers.

In summary, several managerial insights are obtained. First, increasing consumer sensitivity to quality (e.g., by advertising or promotions) is a mutually beneficial



(a) Trends of π_o^*

(b) Trends of π_r^*

(c) Trends of CS

(d) Trends of SW

Fig. 2 Effects of the return rate, γ, on the equilibrium results (policy H: $\alpha = 0.05$, policy C: $\alpha = 0.025$, and policy L: $\alpha = 0.015$)

strategy for the firms because the firms' profits, consumer surplus, and social welfare can be improved. Second, when the IR's cost savings from remanufacturing are insignificant, the IR's competitiveness is reduced; thus, decreasing the rate of return (e.g., the OEM adopts proactive collection to restrict the availability of EOL products to the IR) can avoid the negative effect on consumer surplus. However, when the remanufacturing capacity is already limited, increasing the return rate (e.g., the IR provides discount or trade-in incentives to encourage returns) is beneficial for both the IR and consumers. Third, although providing only low-quality products reduces the expected quality level of remanufactured products perceived by consumers, it is not necessarily harmful to consumer surplus. Specifically, when the cost savings from low-quality products are significant, the scenarios with only low-quality products under ample remanufacturing capacity and with both quality products under limited remanufacturing capacity are available to improve consumer surplus.

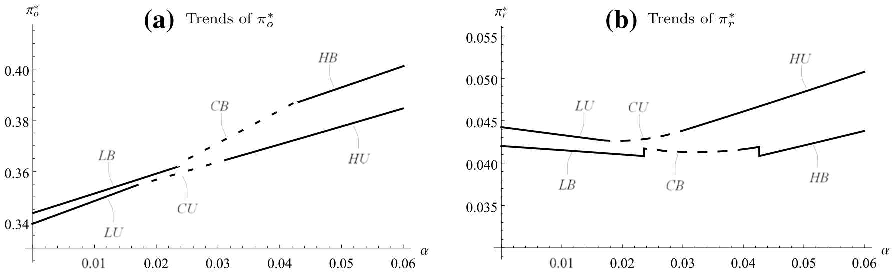
6 Numerical experiments

Thus far, we have analyzed the closed forms of the equilibrium results with respect to the parameters. Now, we turn to numerical analyses of the parameters for the equilibrium quality choices, profits, consumer surplus, and social welfare. Based on prior studies (Atasu et al. 2008; Wu 2015), we consider a representative parametric setting as a base example, as follows: $c = 0.1$, $\beta = 0.03$, $\delta = 0.75$, $\rho = 0.6$, $\tau = 0.05$ and $\kappa = 1.2$.

6.1 Effects of the return rate and consumer sensitivity to quality

We first examine the effects of the return rate γ on the equilibrium results and on IR scenario equilibrium choices, as shown in Fig. 2. We let $\alpha = 0.05$ for scenarios under policy H, $\alpha = 0.025$ for scenarios under policy C and $\alpha = 0.015$ for scenarios under policy L. The corresponding thresholds of γ under the quality policies can be obtained as follows: $\gamma^H = 0.8755$, $\gamma^C = 0.7179$, and $\gamma^L = 0.6920$. The result of $\gamma^H > \gamma^C > \gamma^L$ indicates that when the proportion of high-quality products is higher, the return rate that is required for the IR to have ample capacity is greater. Figure 2 reveals that when the IR remanufacturing capacity is sufficient, the return rate is independent of the equilibrium decisions and thus has no effect on the firms' equilibrium profits, consumer surplus and social welfare. Moreover, the sufficiency of the IR remanufacturing capacity is profitable to the IR, consumers, and social welfare. Thus, the strategy where the IR reduces the quality level to pursue sufficient capacity is advantageous for both the IR's profit and consumer surplus, thus improving social welfare. However, when IR remanufacturing capacity is constrained, a greater return rate decreases the OEM but increases the IR equilibrium profits for all quality policies. An increase in the return rate is also beneficial to consumers because decreasing prices increase consumer surplus. Nevertheless, the return rate is harmful to social welfare because of the significant decrease in OEM profits. Notably, an increase in the return rate even leads π_o^{HB*} to be smaller than π_o^{HU*}, meaning that when the return rate approaches the threshold, the OEM changes its preference to the scenario where the IR has ample capacity. In addition, the difference in IR profits under policies C and L is insignificant, whereas the differences in the OEM profit, consumer surplus, and social welfare are significant. This result indicates that the motivation for the IR to choose the strategy with both the low- and high-quality products is not for individual profit but for the public benefit.

We consider the effect of consumer quality sensitivity α in Fig. 3 and set $\gamma = 0.95$ for the status of unbinding remanufacturing capacity (status U) and $\gamma = 0.6$ for status B. Under these settings, the following conditions of α are obtained: $\alpha^{HU} = 0.03$, $\alpha^{LU} = 0.0169$, $\alpha^{HB} = 0.0426$, and $\alpha^{LB} = 0.0236$. When consumers are more sensitive to quality, new product sales are supported, and thus, the OEM's equilibrium profits increase under any quality policy chosen by the IR. Such an effect is more significant when the IR remanufacturing capacity is constrained. An increase in α also benefits consumers and social. However, an increase in α is not necessarily beneficial to the IR, specifically, when the IR chooses the low-quality policy. When the IR adopts policy L, an increase in α decreases the IR equilibrium profit because the sales margins must be decreased to stimulate consumer purchases. In contrast, when the IR chooses the high-quality policy, an increase in α decreases the intensity of competition such that it can preserve greater sales margins, leading to higher equilibrium profit. Comparing policies L and C, we find that when the IR produces both low- and high-quality products, policy C generally dominates policy L under the same condition regarding the remanufacturing capacity. This insight suggests that when consumers are sensitive to quality, the IR can produce both low- and high-quality products to reduce the harm from consumers' high sensitivity to quality, and this strategy is also favorable to the consumer surplus and social welfare


(a) Trends of π_o^* **(b)** Trends of π_r^*

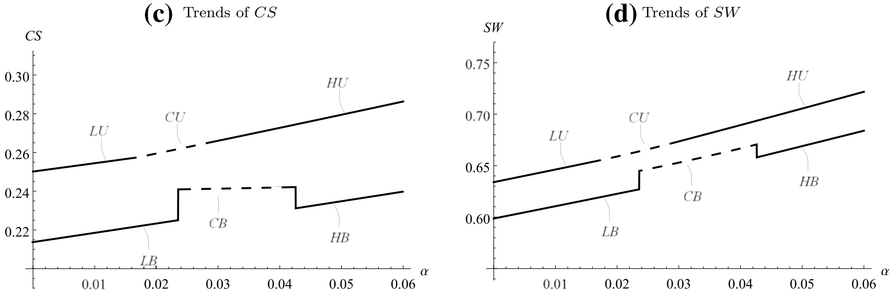
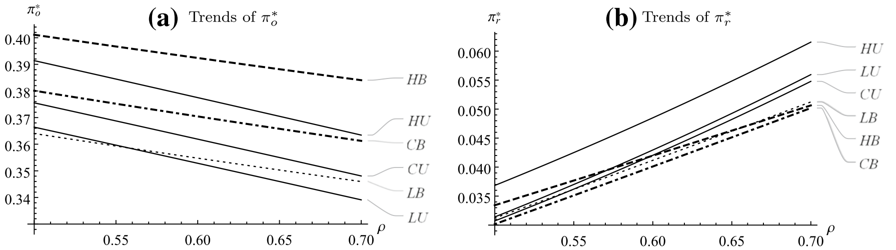

(c) Trends of CS **(d)** Trends of SW

Fig. 3 Effects of the consumers' quality sensitivity, α, on the equilibrium results (status U: $\gamma = 0.95$ and status B: $\gamma = 0.6$)


(a) Trends of π_o^* **(b)** Trends of π_r^*

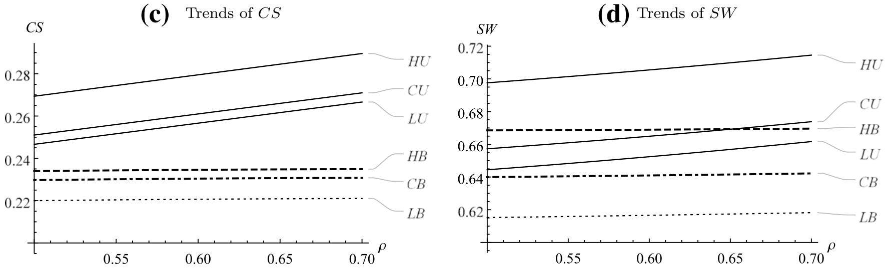
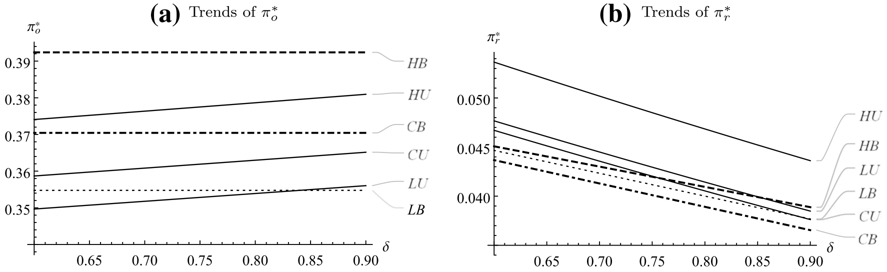

(c) Trends of CS **(d)** Trends of SW

Fig. 4 Effects of the discount factor, ρ, on the equilibrium results for remanufactured products

compared to the pure low-quality strategy. Moreover, when both scenarios *CU* and *LB* are available (as noted in Sect. 4.4), the OEM and the IR prefer to adopt scenario *CU*, which is also more beneficial to consumer surplus and social welfare than scenario *LB*.

(a) Trends of π_o^* **(b)** Trends of π_r^*



(c) Trends of CS **(d)** Trends of SW

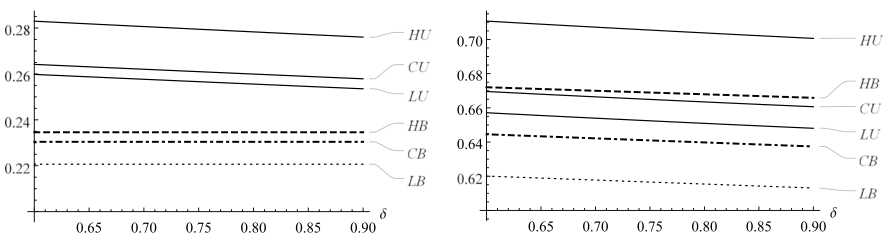


Fig. 5 Effects of the remanufactured product cost savings, δ, on the equilibrium results

6.2 Effects of the parameters associated with remanufactured products

We consider the conditions of α and γ in Sect. 3 and thus set the values of α and γ for all scenarios as follows: $\alpha = 0.05$ and $\gamma = 0.95$ for scenario *HU*; $\alpha = 0.05$ and $\gamma = 0.6$ for scenario *HB*; $\alpha = 0.015$ and $\gamma = 0.95$ for scenario *LU*; $\alpha = 0.015$ and $\gamma = 0.6$ for scenario *LB*; $\alpha = 0.025$ and $\gamma = 0.95$ for scenario *CU*; $\alpha = 0.035$ and $\gamma = 0.6$ for scenario *CB*.

In Fig. 4, we examine the effects of the consumer reservation price discount factor for remanufactured products, i.e., ρ, on the firms' equilibrium profits. In any scenario, a higher consumer reservation price for the remanufactured products decreases the OEM but increases the IR equilibrium profits, particularly when the IR has ample capacity. Regarding IR quality policies, when the IR produces a greater portion of high-quality products, the intensity of competition decreases, which is beneficial to the OEM; hence, scenario *HB*, in which the IR provides all high-quality products with a limited capacity is most favourable to the OEM. When the capacity is ample, IR competitiveness is strong, and the IR therefore makes a large profit, especially when the consumer reservation price for the remanufactured products is higher. Case *HU* is the most favorable to the IR because its remanufactured products are competitive and economy of scale is achieved. However, if the collected quantity is insufficient for producing only high-quality products, the IR should reduce its quality level to pursue ample capacity.

A higher value of ρ increases consumer surplus and social welfare when the IR capacity is sufficiently high, indicating that when the consumer gives the remanufactured products a higher valuation, IR ample remanufacturing capacity is more beneficial to consumers and social welfare. Moreover, consumers prefer scenarios when the IR has ample remanufacturing capacity, followed by when the IR produces a greater portion of high-quality products. This trend occurs because when the IR quantity is chosen at the economy of scale, the remanufactured products will be chosen at the lower equilibrium prices, benefiting consumers. As a result, scenario *HU* is the most advantageous to the IR profits, consumer surplus and social welfare. In addition, reducing the quality level for ample remanufacturing capacity is preferable for both the IR and consumers when the remanufacturing capacity is not sufficiently high to support the pure high-quality strategy.

Figure 5 depicts the effects of the remanufactured product cost savings on the equilibrium results. Greater values of δ lead to lower cost savings of the remanufactured products. When δ increases, the competitiveness of the IR decreases. This result is more significant when the IR has ample capacity. Thus, when the remanufactured product cost savings are small, the IR may change its preference to the scenarios in which its capacity is limited to avoid fierce competition, particularly when low-quality products are produced. Smaller cost savings of the remanufactured products also reduce consumer surplus and social welfare because the IR decreases its quantity and thus increases its prices. However, the cost savings of the remanufactured products have a small impact on the sequence of consumer surplus and social welfare among the scenarios.

7 Summary

In this study, we formulated strategic quality policies for an IR competing with an OEM in a two-period dynamic model and then investigated the firms' equilibrium quantity decisions. Specifically, the IR recovers EOL products that were sold by the OEM in the first period and then sells them as remanufactured products to the market in which consumers are sensitive to the firms' sales prices and average quality levels. The IR chooses high (h) and low (l) quality levels of remanufactured products; i.e., when the high-quality policy is chosen, more EOL products are required for remanufacturing, and then the remanufacturing capacity decreases. Hence, the IR may reduce the average quality level of remanufactured products to increase total production. Correspondingly, the OEM may change the remanufacturing quantity in the first period to lower the competitiveness of the IR. In such an interaction between the OEM and IR, we solve the firms' equilibrium quantities and then derive the conditions regarding the status of the remanufacturing capacity and the IR's quality policy. Finally, we analyze the equilibrium decisions, profits, consumer surplus, and social welfare under different production-quality scenarios.

Our analysis yields many managerial insights. (1) The status of the remanufacturing capacity will change the firms' decisional behaviour. When the IR capacity is ample, the greater cost savings from remanufacturing or reducing quality will induce the OEM to decrease production but will induce the IR to increase production. However, this effect vanishes when the IR capacity is limited. The IR cost advantage is always beneficial to the IR but harmful to the OEM when the IR capacity is ample (i.e., it is independent of the OEM profit when the IR capacity is limited). When the IR capacity is ample, the cost savings from remanufacturing are also beneficial to consumers; otherwise, the cost savings have no impact on consumer surplus. The OEM prefers that the IR capacity is limited because the intensity of competition is mitigated. When the remanufacturing capacity is limited, an increase in the return rate is advantageous to the IR and consumer surplus but harmful to the OEM and social welfare. These results indicate that the IR cost advantage and its impacts on the OEM are based on sufficient capacity. (2) When consumers are more sensitive to the quality level, the intensity of competition will decrease, and then, both the OEM and IR will increase their quantities. Moreover, their profits and consumer surplus will be higher regardless of the status of remanufacturing capacity. An increase in consumer quality sensitivity also causes the high-quality policy to be preferred by both the firms and consumers.

Some findings regarding the IR quality policy are summarized as follows. (3) The OEM profit is more sensitive to the status of the IR capacity; however, the IR profit and consumer surplus are more sensitive to its production-quality policy. In addition, when the IR quality policy is constant, the sufficiency of the remanufacturing capacity is generally beneficial to all parties. The superiority of the pure high-quality policy to the other policies for improving the firms' profits, consumer surplus, and social welfare also relies on ample IR capacity and a high return rate. However, when the remanufacturing capacity is limited by the collected amount, the IR changes its preference to providing low-quality products for ample capacity, and this action is also beneficial to consumers but harmful to the OEM. (4) When the remanufactured products are more competitive because they possess greater consumer valuation, they are beneficial to the IR, the consumers and society but are harmful to the OEM. Moreover, the phenomenon that the pure low-quality policy will be more profitable to the IR than the mixed-quality policy exists under the following situations: when the remanufactured products are more competitive, when the consumers are insensitive to the quality, and when the cost savings from remanufacturing are large.

This paper has made several assumptions, and relaxing these assumptions may provide more managerial insights. First, we focus on a two-period model that has been extensively adopted in the literature (Majumder and Groenevelt 2001; Debo et al. 2005, 2006; Ferguson and Toktay 2006; Atasu et al. 2008; De Giovanni and Zaccour 2014). This paper could be extended by considering a multiperiod model; however, such a model would be complex, and thus, it is likely to be analytically intractable. Second, we considered the discrete quality choice with two levels following the work of Melumad and Ziv (2004) who indicated that this setting is sufficient for investigating a firm's quality choice and simplifies the exposition. Thus, another possible direction is to extend our model to regard a continuous bounded subset of the quality level. Third, we revealed that in some situations, the OEM and IR may not have common preferred scenarios. Thus, it would be interesting to expand the current model by considering the strategic reactions of the OEM, and thus the OEM and IR will interact on both strategic and operational levels.

Acknowledgements This research was partially supported by the Ministry of Science and Technology, Taiwan, ROC, under #MOST 108-2221-E-006-222-MY3.

Appendix: Derivation of the condition for duopoly in the second period

For simplicity, we let $\mathbb{D}_i \equiv p_i - \alpha\,\chi_i$, where $i \in \{o, r\}$; thus, the consumer utilities can be rewritten as $U_o = \theta - \mathbb{D}_o$ and $U_r = \rho\,\theta - \mathbb{D}_r$. Each consumer purchases product i, $i \in \{o, r\}$, when $U_i > 0$ and $U_i > U_{i'}$, where $i' \in \{o, r\}/i$. Solving $U_o = 0$ and $U_r = 0$ for θ, we obtain two points, $\theta_o \equiv \mathbb{D}_o$ and $\theta_r \equiv \mathbb{D}_r/\rho$, respectively. There are two possible cases: $\theta_o \geq \theta_r$ and $\theta_o < \theta_r$. However, under the case $\theta_o < \theta_r \Leftrightarrow \mathbb{D}_o < \mathbb{D}_r/\rho$, $U_o > U_r$ always holds because $U_o = \theta - \mathbb{D}_o > \theta - \mathbb{D}_r/\rho > \rho(\theta - \mathbb{D}_r/\rho) = U_r$. Hence, we know that the duopoly does not exist under the case $\theta_o < \theta_r$. The condition of $\theta_o \geq \theta_r \Leftrightarrow \mathbb{D}_o \geq \mathbb{D}_r/\rho$, called "Condition 1", must be held for duopoly, corresponding to the works of (Chiang et al. 2003) and (Atasu et al. 2008).

Next, we derive the indifferent point by solving $U_o = U_r$ for θ and obtain $\theta_{ro} \equiv (\mathbb{D}_o - \mathbb{D}_r)/(1-\rho)$. Because $\partial U_o/\partial\theta > \partial U_r/\partial\theta$, $U_r \geq U_o$ if $\theta \leq \theta_{ro}$, and $U_r < U_o$ otherwise. Hence, consumers located between θ_r and θ_{ro} choose remanufactured products, and consumers located between θ_{ro} and 1 choose new products. Notably, we can observe that the total demand is dependent of θ_r but independent of θ_o. For the existence of duopolistic competition, we have to verify that θ_{ro} is located between θ_r and 1. (1) It is easily to verify that $\theta_{ro} \geq \theta_r$ because Condition 1: $\mathbb{D}_o \geq \mathbb{D}_r/\rho \Rightarrow \theta_{ro} - \theta_r = (\rho\mathbb{D}_o - \mathbb{D}_r)/((1-\rho)\rho) \geq 0$. (2) For $\theta_{ro} \leq 1$, we can obtain the condition $\rho - (1 - \mathbb{D}_o + \mathbb{D}_r) \leq 0$, called "Condition 2".

Condition 1 and Condition 2 must hold throughout the paper. Then, we incorporate the forms of prices, i.e., $p_o = 1 + \alpha - q_o - \rho\left(q_{rh} + q_{rl}\right)$ and $p_r = \rho\left(1 - \left(q_o + q_{rh}\right)\right) + \alpha\,q_{rh}/(q_{rh} + q_{rl}) - \rho q_{rl}$, into Condition 1 and Condition 2, and the conditions can be rewritten as follows:

$$\text{Condition 1: } \mathbb{D}_o \geq \mathbb{D}_r/\rho \Leftrightarrow (1-\rho)\rho\left(q_{rh} + q_{rl}\right) \geq 0,$$
$$\text{Condition 2: } \rho - (1 - \mathbb{D}_o + \mathbb{D}_r) \leq 0 \Leftrightarrow (1-\rho)q_o \leq 0.$$

Clearly, Condition 1 innately holds. For Condition 2, we derive the best-response decision of p_o, i.e., $p_o^\dagger \equiv \frac{1}{2}\left(\alpha - c - \rho\left(q_{rh} + q_{rl}\right) + 1\right)$, by maximizing Eq. (2). Incorporating $p_o^\dagger$ into Condition 2 implies that $\rho - (\alpha - c + 1)/(q_{rh} + q_{rl}) \leq 0$ must be true. As a result, we assume that the condition $\rho - (\alpha - c + 1)/(q_{rh} + q_{rl}) \leq 0$, is always true throughout the paper.

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