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Entering the high-end market by collecting and remanufacturing a competitor's high-end cores[☆]

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ABSTRACT

Motivated by the smartphone industry, this paper studies a duopoly channel consisting of a high-end firm and a low-end firm. The high-end firm sells its own brand at a high profit margin. The low-end firm sells its own brand at a low profit margin, but can choose to differentiate by collecting and remanufacturing high-end cores, thereby entering the more lucrative high-end market. We investigate how the equilibrium strategies of both firms are influenced by the cost structure and customers' valuation. We derive a condition for the low-end firm to engage in remanufacturing high-end cores, and show how the high-end firm reacts to limit the loss of market share.

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1. Introduction

The smartphone market is huge and fiercely competitive, especially for low-end firms whose brand is valued less because of technology. As a report by Strategy Analytics shows, 1.46 billion smart phones were sold in 2017, and global smartphone industry revenues were \$120 billion during the fourth quarter of 2017. Apple held 19% of the global smartphone market share, but accounted for 87% of the revenues. On the contrary, all other companies together, including Samsung and Huawei, had nearly 80% of the marketshare but only 13% of the revenues [1]. Profit margins are slim in the low-end market, and top smartphone vendors in China even operate at a loss. For example, in 2016, the net profit of Chinese smartphone vendor, Smartisan Technology, was -0.24 billion RMB [2]. Entering the much more profitable high-end market is therefore appealing to low-end firms. However, upgrading their own brand requires considerable investment in both R&D and marketing.

An alternative for a low-end firm is to start collecting and remanufacturing used high-end (name-brand) products, next to producing its low-end products. The high/low-end products here refer to the quality, which is recognized by customers as brand power. From the point of view of the firms, the high/low-end firm's technology determines the brand value, so the high/low-end firm sells high/low brand value products. Meizu, a Chinese smart-

phone manufacturer recently started to cooperate with a Chinese smart-phone recycle platform, named Aihuishou, to collect used iPhones and sell remanufactured iPhones. More generally, by remanufacturing high-end products, a low-end firm may simultaneously increase its market share and profit margin. Whether this is indeed possible depends on market characteristics, particularly the (re)manufacturing cost and consumer preference. In this paper, we explore under what conditions it is profitable for a low-end firm to start collecting and remanufacturing used high-end products. Moreover, we show how the increasing competition affects the pricing strategies of both the low-end firm and the high-end firm.

Competition between new and remanufactured products has been intensively studied in the literature. However, existing research assumes that an OEM and/or an independent operator remanufacture(s) used products, and that there only exists the competition between remanufactured products and new products. To best of our knowledge, we are the first to consider the scenario that the low-end firm remanufactures used high-end products, besides manufacturing its own brand, to compete with the high-end firm in the market. As the remanufactured product competes with both the low-end and high-end products in this setting, it is more challenging to characterize the optimal strategies of both the low-end firm and the high-end firm than in existing studies. We develop a game theoretical model with utility-based demand functions, where customers are heterogeneous in their product valuations and use the Stackelberg game to model the dynamic decision process. We investigate how the equilibrium strategies of both firms are influenced by the cost structure and customers' valuation. We derive a condition for the low-end firm to engage in

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remanufacturing high-end cores, and show how the high-end firm reacts to limit the loss of market share.

The rest of the paper is structured as follows. In Section 2, we discuss the related literature. In Section 3, we describe the system. In Section 4, we present a benchmark model without remanufacturing. Section 5 includes the remanufacturing option, and determines the optimal strategies for both firms. Section 6 presents a numerical study. In Section 7, we study the scenario that the OEM also engages in remanufacturing. We conclude in Section 8.

2. Literature review

This research is related to two stream of literature: market segmentation and remanufacturing competition.

The literature on market segmentation under duopoly [3–5] examines the optimal pricing and quality position of an independent product in a market with heterogeneous consumers. Firms face increased quality cost when customers differ in both quality preference and taste (which usually relates to brand preference). Mendelson and Parlaktürk [6] extend the product line variety choice results to a duopoly with asymmetric firms.

For the literature on remanufacturing competition, closed-loop supply chain management has attracted a lot of attention since the 1990s, and a number of reviews have appeared. Moritz et al. [7] provide a critical review of the early quantitative models, and Guide Jr and Van Wassenhove [8] describe the evolution of closed-loop supply chain from a business perspective. Souza [9] classifies closed-loop supply chain research into strategic, tactical, and operational issues.

Ferguson and Toktay [10] show that core collection (cost and quantity) and endogenous customer willingness-to-pay for new/remanufactured products are the driving factors in deciding whether to produce remanufactured and/or new products. Therefore, at the operational and tactical level, an important issue in remanufacturing is the optimal core acquisition plan for product returns [11–13], yield uncertainty management [14,15], and production process control for remanufacturing [16,17]. Different from these studies, we consider the strategic aspects of competition in and from remanufacturing. In what follows, we therefore dive into the two main streams of research on competition in remanufacturing: an OEM faces indirect competition from an independent operator (IO); or an OEM faces direct competition from another OEM.

Under the assumption that the remanufactured product by an IO is distinguished by customers, a number of studies consider the indirect competition between an OEM and an IO. Majumder and Groenevelt [18] derive the Nash equilibrium of price and quantity under different reverse logistic settings. Ferrer and Swaminathan [19] consider the effect of demand preferences on competition. Debo et al. [20] study the joint pricing and technology decision for a monopoly OEM that considers introducing a remanufacturable product, and first show that this can not only reduce cost, but also expand the market. They then show that under competition between the OEM and an IO, the optimal remanufacturability level is lower than that for the monopoly model. Ferguson and Toktay [10] continue this line of research and find that an OEM can deter competition from an IO by controlling the quantity of cores available to the IO. Webster and Mitra [21], Mitra and Webster [22], Esenduran et al. [23] study the effect of legislations and regulations on remanufacturing under the competition between an OEM and an IO. Wu [24] studies how the product design decision influences the price decision of an OEM in competing with an IO. Subramanian et al. [25] show that competition between an OEM and an IO may shift the commonality decision of the OEM in its product line design. Örsdemir et al. [26] describe, from the point of view of an OEM, how competition from an IO affects the quality choice of

new products. Bulmus et al. [27] optimize both pricing and cores collection decisions.

For the direct competition of two OEMs, Heese et al. [28] consider the profitability condition for an OEM to adopt a remanufacturing strategy. With a Stackelberg model, they find that remanufacturing is especially profitable for the first moving firm. In their study, a customer is able to sell a used product in secondary market, but not able to differentiate between new and remanufactured products. Atasu et al. [29] consider the situation where products can be differentiated, but assume that a green segment of the market views them as equally valued. They find that remanufacturing can be an effective strategy to deter a competitor when the cost of remanufacturing is sufficient low. Instead of assuming a green segment customer, Oraopoulos et al. [30] examine a situation in which two OEMs directly compete in the primary market by selling new products and charge a relicensing fee on their remanufactured products in the secondary market. Mitra [31] also considers direct competition, but assumes that remanufactured products are sold in a secondary market, which implies only one-way substitutability between the new and remanufactured products of a single manufacturer. Using a behaviour study to estimate demand, Raz et al. [32] investigate the impact of remanufacturing for product-service firms under direct competition. They assume that one firm adds a remanufactured product into its product line and show that remanufacturing reduces price and expands the total market, which increases both firms' profits.

Different from the above-reviewed literature, the contributions of this paper are as follows. Motivated by the discussed recent developments in the smart phone market, we analyze the situation where a low-end firm may remanufacture used high-end products. We study product differentiation not only between new and remanufactured products, but also between high-end and low-end products. Our study provides insights into when and to what extent a low-end firm should engage in remanufacturing and how the high-end firm should response to such a threat.

3. System description

We consider a duopoly setting with a high-end firm and a low-end firm. The latter considers to sell (previous version of) remanufactured high-end cores, next to its own low-end brand of new products. The high-end firm is not considering to sell remanufactured products, at least not under the same brand. Doing so would come at the risk of cannibalizing new product sales and a corresponding revenue loss. The high-end firm could alternatively consider to sell remanufactured product in a different market, but this would not affect competition in the considered market where customers may choose to substitute a new product with a remanufactured product and is out of our scope. Although a high-end firm can take actions to prevent its products from being de-branded by competitors, this may not be successful in practice. For example, Gazelle¹ and Decluttr² are able to collect and refurbish used iPhones.

From now on, we will refer to new high-end products, remanufactured high-end products, and new low-end products as H, R, and L, respectively. As Ferguson and Toktay [10], we assume that the customer's willingness-to-pay θ is heterogeneous and uniformly distributed on the interval $[0,1]$, and that R is valued at a fixed fraction, σ , of H. Similarly, L is valued at a fraction α of H. To reflect the situation with the considerable brand/quality advantage of the high-end firm, as discussed in the introduction, we as-

¹ <https://www.gazelle.com/>.

² https://www.decluttr.com/?source=aw&utm_source=323691&utm_medium=awin&utm_campaign=ShareASale.com%2C+Inc.&awc=8053_1555513067_e016d9aa70b232973426d2dae1a40eb9.

Table 1
Notation

Notation	Definition
Model Parameters	
α	customer value discount for product L
σ	customer value discount for product R
c_H	unit manufacturing cost of product H
c_R	unit acquisition and remanufacturing cost of product R
c_L	unit manufacturing cost of product L
Decision Variables	
p_H	unit price of product H
p_R	unit price of product R
p_L	unit price of product L
q_H	sales of product H
q_R	sales of product R
q_L	sales of product L

sume that $0 < \alpha < \sigma < \theta < 1$. In the remanufacturing literature, when only the IO sells a remanufactured product, this product is valued less by customers in comparison to the new product by the OEM, e.g., see [20]. When both the OEM and IO sell remanufactured products, the product by the IO is regarded as a low-end product and is valued at a fraction of the product remanufactured by the OEM, e.g., see [19]. The vertically differentiated market assumption is widely used in the remanufacturing literature when customers are able to differentiate new and remanufactured products [19,29,33,34].

We denote the prices of H, R, and L by p_H , p_R and p_L , respectively. The associated net customer utilities of buying H, R, and L are given by $U^H = \theta - p_H$, $U^R = \sigma\theta - p_R$, and $U^L = \alpha\theta - p_L$, respectively. Customers buy the product that maximizes their net utility (or not at all). We normalize the market size to 1 and derive the market shares for H, R, and L in Sections 4 and 5. Table 1 lists the notations.

The high-end firm and the low-end firm engage in Stackelberg competition. The high-end firm has market power over the low-end firm, and so acts as a Stackelberg leader and first decides on p_H . Then, the low-end firm, acting as a Stackelberg follower, decides on p_L and p_R . The prices jointly determine the sales based on customer utility maximization. We assume that there is ample supply of cores of high-end products available to the low-end firm. This is justified since there are typically many older, used versions of a product such as an iPhone in the market when a new version is introduced. For example, Jia et al. [35] show that the number of returns increases as the product ages. Moreover, Raz et al. [32], Ovchinnikov et al. [36] show that older versions of a product, such as the iPhone 3, become available in large numbers when the new generation, such as the iPhone 4, is introduced. Modelling the relation between historic sales figures of previous versions and the possibly limited availability of cores would make our model and analysis much more complex. Instead, we assume that the remanufacturing cost c_R is set large enough to attract a sufficient number of cores. The profit functions of both firms are given as follows, i.e.,

$$\begin{aligned}\pi_L(p_L, p_R) &= q_L(p_L - c_L) + q_R(p_R - c_R), \\ \pi_H(p_H) &= q_H(p_H - c_H).\end{aligned}\quad (1)$$

We derive the equilibrium by backward induction. We first determine the optimal (reaction) prices of the low-end firm, p_L and p_R . Then, we determine the optimal price of the high-end firm. Further, to avoid unrealistic solutions, we assume that H is always in the market. That is, the price of H is set such that the corresponding market share is positive.

In the following section, we first consider the benchmark without a remanufacturing option and then study the case with such an option.

Fig. 1. Market situation without a remanufacturing option

4. No remanufacturing option

Without remanufactured products in the market, customers have the following three choices: (i) buy H; (ii) buy L; (iii) do not buy at all. A customer buys H if $U^H \geq 0$ and $U^H \geq U^L$, i.e. $\theta \geq \max\{\frac{p_H - p_L}{1 - \alpha}, p_H\}$. A customer prefers to buy L if $U^L \geq 0$ and $U^L \geq U^H$, i.e. $\frac{p_L}{\alpha} \leq \theta \leq \frac{p_H - p_L}{1 - \alpha}$. Recalling the assumption that H is always in the market, we distinguish the following: when the price of the high-end firm is sufficiently low ($p_H < \frac{p_L}{\alpha}$), only H is in the market; when $p_H > \frac{p_L}{\alpha}$, both H and L are in the market. This leads to the demand specification in Lemma 1.

Lemma 1. When there is no remanufacturing option, demand q_L for product L and demand q_H for product H are as follows:

- (i) if $p_H < \frac{p_L}{\alpha}$, then only H is in the market and $q_H = 1 - p_H$;
- (ii) if $p_H \geq \frac{p_L}{\alpha}$, then both H and L are in the market and $q_H = \frac{1 - \alpha - p_H + p_L}{1 - \alpha}$, $q_L = \frac{\alpha p_H - p_L}{\alpha(1 - \alpha)}$.

PROOF: See Appendix A. The consumer behaviour in each condition is summarized in Fig. 1.

Atasu et al. [29] study direct competition between two OEMs under Bertrand competition. They assume that the remanufactured product is valued less by customers than the competitor's new product. The green segment customers only purchase remanufactured products and primary customers choose among remanufactured products and new products depending on their utility. By comparing to a benchmark without remanufacturing, they analyze the effect of remanufacturing on competition. They show that the profitability of remanufacturing depends on the cost advantage, the green segment size, and the degree of competition.

Our work is similar to the work by Atasu et al. [29] with two important differences in our setting. In this model, we do not consider the green segment customer and model Stackelberg competition. We obtain that when

$$c_L \leq \alpha \frac{(2 - \alpha)c_H + 2(1 - \alpha)}{4 - 3\alpha}, \quad (2)$$

the equilibrium decision and the corresponding profit of both firm are given as follows:

$$\begin{aligned}p_L^* &= \frac{\alpha(2 - \alpha)c_H + (4 - \alpha)c_L + 2\alpha(1 - \alpha)}{4(2 - \alpha)}, \\ p_H^* &= \frac{(2 - \alpha)c_H + c_L + 2(1 - \alpha)}{2(2 - \alpha)}, \\ q_L^* &= \frac{\alpha(2 - \alpha)c_H - (4 - 3\alpha)c_L + 2\alpha(1 - \alpha)}{4\alpha(1 - \alpha)(2 - \alpha)}, \\ q_H^* &= \frac{2(1 - \alpha) - (2 - \alpha)c_H + c_L}{4(1 - \alpha)}, \\ \pi_L^* &= \left[\frac{\alpha(2 - \alpha)c_H - (4 - 3\alpha)c_L + 2\alpha(1 - \alpha)}{4(2 - \alpha)} \right]^2 \frac{1}{\alpha(1 - \alpha)},\end{aligned}$$

Fig. 2. Market situation with a remanufacturing option

$$\pi_H^* = \frac{[2(1-\alpha) - (2-\alpha)c_H + c_L]^2}{8(1-\alpha)(2-\alpha)}.$$

If (2) does not hold, then the low-end firm will exit the market.

5. Remanufacturing option

To find the equilibrium of this scenario, we first characterize the optimal strategy of the low-end firm given the high-end firm's strategy and then go backwards to derive the optimal strategy of the high-end firm.

As the leader of the Stackelberg game, the high-end firm first decides on p_H . We aim to find the optimal response for the low-end firm to adopt the remanufacturing strategy. Note that if a customer purchases a remanufactured product, the corresponding utility is U^R , where $U^R = \sigma\theta - p_R$. Similar to the analysis in Section 4, we obtain the following lemma that gives the demand function under different conditions.

Lemma 2. Given the prices of products L, R and H, demands (only given when positive, i.e., when a product is in the market) are as follows.

- (i) if $p_H < \frac{p_R}{\sigma}$ and $p_H < \frac{p_L}{\alpha}$, then $q_H = 1 - p_H$;
- (ii) if $\frac{p_L}{\alpha} < p_H < \frac{(1-\alpha)p_R - (1-\sigma)p_L}{\sigma - \alpha}$, then $q_H = \frac{1 - \alpha - p_H + p_L}{1 - \alpha}$ and $q_L = \frac{\alpha p_H - p_L}{\alpha(1 - \alpha)}$;
- (iii) if $p_R < \frac{\sigma p_L}{\alpha}$ and $\frac{p_R}{\sigma} < p_H$, then $q_H = \frac{1 - \sigma - p_H + p_R}{1 - \sigma}$ and $q_R = \frac{\sigma p_H - p_R}{\sigma(1 - \sigma)}$;
- (iv) if $p_R > \frac{\sigma p_L}{\alpha}$ and $\frac{(1-\alpha)p_R - (1-\sigma)p_L}{\sigma - \alpha} < p_H$, then $q_H = \frac{1 - \sigma - p_H + p_R}{1 - \sigma}$, $q_R = \frac{p_H - p_R}{1 - \sigma} - \frac{p_R - p_L}{\sigma - \alpha}$ and $q_L = \frac{\alpha p_R - \sigma p_L}{\alpha(\sigma - \alpha)}$.

PROOF: See A.1. The consumer behaviour in each condition is summarized in Fig. 2.

The four conditions with associated quantities as in Lemma 2 correspond to the following strategies for the low-end firm, given the price of the high-end firm acting as the Stackelberg leader: (i) exit the market; (ii) only produce L; (iii) only produce R; (iv) produce both R and L. The associated profits for the low-end firm are obtained by inserting the results of Lemma 2 into (1). In Appendix B, we prove that this profit function is concave in both p_L and p_R , and derive the optimal response of the low-end firm as describe in the following proposition.

Proposition 3. Given the price of the high-end firm, the optimal response of the low-end firm is describe by the following four cases.

- Case 1. When $c_R > \sigma p_H$ and $c_L > \alpha p_H$, exit the market.
- Case 2. When $\frac{(\sigma - \alpha)p_H + (1 - \sigma)c_L}{1 - \alpha} < c_R$ and $c_L \leq \alpha p_H$, produce L only; $p_L^* = \frac{\alpha p_H + c_L}{2}$, $q_L^* = \frac{\alpha p_H - c_L}{2\alpha(1 - \alpha)}$, $\pi_L^* = \frac{(\alpha p_H - c_L)^2}{4\alpha(1 - \alpha)}$.
- Case 3. When $\frac{\sigma c_L}{\alpha} < c_R \leq \frac{(\sigma - \alpha)p_H + (1 - \sigma)c_L}{1 - \alpha}$, produce L and R; $p_L^* = \frac{\alpha p_H + c_L}{2}$, $p_R^* = \frac{\sigma p_H + c_R}{2}$, $q_L^* = \frac{\alpha c_R - \sigma c_L}{2\alpha(\sigma - \alpha)}$, $q_R^* = \frac{(\sigma - \alpha)p_H - (1 - \alpha)c_R + (1 - \sigma)c_L}{2(1 - \sigma)(\sigma - \alpha)}$, $\pi_L^* = \frac{(\alpha p_H - c_L)(\alpha c_R - \sigma c_L)}{4\alpha(\sigma - \alpha)} + \frac{(\sigma p_H - c_R)[(\sigma - \alpha)p_H - (1 - \alpha)c_R + (1 - \sigma)c_L]}{4(1 - \sigma)(\sigma - \alpha)}$.

Table 2

Conditions for high-end policy cases.

Case	Condition
H^1	$c_{R5} < c_R$, $c_{L2} < c_L$
H^2	$c_{R4} < c_R \leq c_{R5}$, $c_R \leq c_{R1}$
H^3	$c_{R1} < c_R$, $c_{L1} < c_L \leq c_{L2}$
$H\&L^1$	$c_{R3} < c_R$, $c_L \leq c_{L1}$
$H\&L^2$	$c_{R2} < c_R \leq c_{R3}$, $c_R \geq c_{R1}$
$H\&R$	$c_R \leq c_{R4}$, $c_R \leq c_{R1}$
$H, R\&L$	$c_{R1} < c_R \leq c_{R2}$

Table 3

Critical values for high-end policy.

$c_{R1} = \frac{\sigma c_L}{\alpha}$
$c_{R2} = \frac{(\sigma - \alpha)(\sigma - \alpha)c_H + 2(1 - \sigma)(2 - \alpha)c_L + 2(1 - \sigma)(\sigma - \alpha)}{4 + 2\alpha\sigma - 3\alpha - 3\sigma}$
$c_{R3} = \frac{(2 - \alpha)(\sigma - \alpha)c_H + (4 + 2\alpha\sigma - 3\alpha - 3\sigma)c_L + 2(1 - \alpha)(\sigma - \alpha)}{2(1 - \alpha)(2 - \alpha)}$
$c_{R4} = \frac{\sigma(2 - \sigma)c_H + 2\sigma(1 - \sigma)}{4 - 3\sigma}$
$c_{R5} = \frac{\sigma(c_H + 1)}{2}$
$c_{L1} = \frac{\alpha(2 - \sigma)c_H + 2\alpha(1 - \alpha)}{4 - 3\alpha}$
$c_{L2} = \frac{\alpha(c_H + 1)}{2}$

- Case 4. When $c_R \leq \frac{\sigma c_L}{\alpha}$ and $c_R \leq \sigma p_H$, produce R only; $p_R^* = \frac{\sigma p_H + c_R}{2}$, $q_R^* = \frac{\sigma p_H - c_R}{2\sigma(1 - \sigma)}$, $\pi_L^* = \frac{(\sigma p_H - c_R)^2}{4\sigma(1 - \sigma)}$.

PROOF: See Appendix B.

The qualitative interpretation of Proposition 3 is straightforward. When producing L or R becomes (relatively) less costly, production of either type increases.

So far, we have only considered the optimal response of the low-end firm, given the price set by the high-end firm, which led to the four cases in Proposition 3. To complete the characterization of the optimal pricing strategies for both firms, we next derive the optimal pricing decision for the high-end firm. Given the low-end firm's optimal response in Proposition 3 and the demand function in Lemma 2, we can rewrite the profit function of the high-end firm in (1) as follows,

$$\pi_H(p_H) = \begin{cases} (1 - p_H)(p_H - c_H), & \text{if } p_H \leq \frac{c_L}{\alpha} \text{ and } p_H \leq \frac{c_R}{\sigma}; \\ (1 - \frac{(2 - \alpha)p_H - c_L}{2(1 - \alpha)})(p_H - c_H), & \text{if } \frac{c_L}{\alpha} < p_H \leq \frac{(1 - \alpha)c_R - (1 - \sigma)c_L}{\sigma - \alpha}; \\ (1 - \frac{(2 - \sigma)p_H - c_R}{2(1 - \sigma)})(p_H - c_H), & \text{if } \frac{(1 - \alpha)c_R - (1 - \sigma)c_L}{\sigma - \alpha} < p_H \text{ and } \frac{c_R}{\sigma} < p_H. \end{cases} \quad (3)$$

As proven in Appendix C, $\pi_H(p_H)$ is concave in p_H , and as it turns out that there are seven cases with different closed-form expressions of the optimal price p_H^* depending on the values of cost parameters. The seven cases characterize the optimal policy of the low-end firm and the high-end firm. Table 2 defines all seven cases, using additional notation as provided in Table 3, where the case names in Table 2 indicate which products are in the market. The equilibrium prices and quantities for both firms, also derived in Appendix C, are given in Table 4. We remark that, as indicated by the case names, some cases (namely with the same letters) imply the same strategy type, e.g., H^1 , H^2 and H^3 are all cases

Table 4
Equilibrium prices and quantities for both firms.

Case	High-end Firm	Low-end Firm
H^1	$p_H^* = \frac{1+c_H}{2}; q_H^* = \frac{1-c_H}{2}$	
H^2	$p_H^* = \frac{c_L}{\sigma}; q_H^* = 1 - \frac{c_L}{\sigma}$	
H^3	$p_H^* = \frac{c_L}{\sigma}; q_H^* = 1 - \frac{c_L}{\sigma}$	
$H\&L^1$	$p_H^* = \frac{2(1-\alpha)+(2-\alpha)c_H+c_L}{4(1-\alpha)}$	$p_L^* = \frac{\alpha(2-\alpha)c_H+(4-\alpha)c_L+2\alpha(1-\alpha)}{4(2-\alpha)}$
	$q_H^* = \frac{2(1-\alpha)-(2-\alpha)c_H+c_L}{4(1-\alpha)}$	$q_L^* = \frac{\alpha(2-\alpha)c_H-(4-3\alpha)c_L+2\alpha(1-\alpha)}{4\alpha(1-\alpha)(2-\alpha)}$
$H\&L^2$	$p_H^* = \frac{(1-\alpha)c_R-(1-\sigma)c_L}{2(\sigma-\alpha)}$	$p_L^* = \frac{\alpha(1-\alpha)c_R+(\sigma\alpha+\sigma-2\alpha)c_L}{2(\sigma-\alpha)}$
	$q_H^* = \frac{2(\sigma-\alpha)-(2-\alpha)c_R+(2-\sigma)c_L}{2(\sigma-\alpha)}$	$q_L^* = \frac{\alpha c_R-\sigma c_L}{2\alpha(\sigma-\alpha)}$
$H\&R$	$p_H^* = \frac{2(1-\sigma)+(2-\sigma)c_H+c_R}{4(1-\sigma)}$	$p_R^* = \frac{\sigma(2-\sigma)c_H+(4-\sigma)c_R+2\sigma(1-\sigma)}{4(2-\sigma)}$
	$q_H^* = \frac{2(1-\sigma)-(2-\sigma)c_H+c_R}{4(1-\sigma)}$	$q_R^* = \frac{\sigma(2-\sigma)c_H-(4-3\sigma)c_R+2\sigma(1-\sigma)}{4\sigma(1-\sigma)(2-\sigma)}$
$H, R\&L$	$p_H^* = \frac{2(1-\sigma)+(2-\sigma)c_H+c_R}{4(1-\sigma)}$	$p_L^* = \frac{2\alpha(1-\sigma)+\alpha(2-\sigma)c_H+\alpha c_R+2(2-\sigma)c_L}{4(2-\sigma)}$
	$q_H^* = \frac{2(1-\sigma)-(2-\sigma)c_H+c_R}{4(1-\sigma)}$	$p_R^* = \frac{\sigma(2-\sigma)c_H+(4-\sigma)c_R+2\sigma(1-\sigma)}{4(2-\sigma)}$
		$q_L^* = \frac{\alpha c_R-\sigma c_L}{2\alpha(\sigma-\alpha)}$
		$q_R^* = \frac{2(1-\sigma)(\sigma-\alpha)+(2-\sigma)(\sigma-\alpha)c_H+2(1-\sigma)(2-\sigma)c_L+(4+2\alpha\sigma-3\sigma-3\alpha)c_R}{4(1-\sigma)(\sigma-\alpha)(2-\sigma)}$

for which only product H is in the market. The consideration of boundary conditions leads to the existence of multiple cases for some strategy types, as shown in Appendix C. So, although there are four strategy types, we use seven cases to characterize the optimal policy.

From Table 4, we obtain the four following scenarios depending on which types of products are in the market.

- If only H is in the market, corresponding to Cases H^1 , H^2 and H^3 , the high-end firm has a monopoly. However, only for Case H^1 , the high-end firm is able to charge the monopoly price. For Cases H^2 and H^3 , the high-end firm has to offer a lower price in order to deter the entry of L and R.
- If both H and L are in the market, corresponding to Cases $H\&L^1$ and $H\&L^2$, the high-end and low-end firms are engaged in a duopoly scenario. Case $H\&L^1$ is the same as the benchmark case. For Case $H\&L^2$, under the threat of R, the high-end firm's price is lower than that of Case $H\&L^1$ so as to prevent the entry of R.
- If both H and R are in the market, corresponding to Case $H\&R$, the high-end firm and the low-end firm are also engaged in a duopoly scenario. The high-end firm's price is lower than that of the benchmark case so as to prevent the entry of L.
- If H, R and L are in the market, corresponding to Case $H, R\&L$, the high-end firm adopts the same price strategy as that of Case $H\&R$. The low-end firm also adopts the same price strategy for R as that of Case $H\&R$. Thus, when the high-end firm cannot successfully deter the entry of R, it is optimal for the high-end firm to adopt the same price strategy no matter whether the low-end firm produces L or not. However, the low-end firm needs to strategically price L so as to maintain profitable under the competition of R and H.

The above price and product strategies can be observed in business practice. For example, Tesla, a high-end electric car manufacturer, sold Model X in China at a relatively high price at the very beginning. Later, a Chinese electric car manufacturer introduces its own products into the market, at a time when used Tesla cars also started to become available in the market³. As a result, the sales of Tesla in China decreases significantly, to which Tesla responded by reducing the price of a new car⁴. Similarly, when the first generation iPhone was introduced, it was sold at a relatively high price. Later, other smartphone manufacturers began to produce similar phones, such as i9000 of Samsung and HTC dream,

Fig. 3. Optimal strategy: influence of the production costs

and used iPhones also entered the market. Apple lowered the price and started introducing a new generation iPhone.

Because of the many cases, the optimal decisions as listed in Table 4 do not offer direct insights. Fortunately, we can display all corresponding regions graphically based on the production cost c_L and c_R in Fig. 3. The case/region names (see also Table 2) indicate what products (H, L and/or R) are in the market. The boundary conditions are listed in Table 3. As shown in Fig. 3, the low-end firm is more likely to produce L and/or R as this becomes less costly. Furthermore, the diagonal boundaries highlight the internal competition effects. As $c_L(c_R)$ increases, producing R(L) becomes profitable for larger values of $c_R(c_L)$. Indeed, as we will show in the next section numerically, the production quantity of L(R) also increases for a fixed value of $c_L(c_R)$ as $c_R(c_L)$ increases. In that section we also describe how the high-end firm lowers its price to limit competition.

6. Effects of remanufacturing on competition and profits

Our study is the first to consider remanufacturing option for the low-end firm. In our numerical analysis, we therefore focus on the effects of the unit remanufacturing cost c_R on competition and profits. The cost parameter are derived from the industry practice and normalized to obtain comparable results. We set $c_H = 0.37$ (based on a Statista's report which states that the cost to manufacture an \$999 iPhone X is estimated at \$370.25) and $c_L = 0.1$ (based

³ <https://www.tesla.com/inventory/used/ms>.

⁴ <https://www.bloomberg.com/news/articles/2019-07-16/tesla-says-it-cut-prices-of-vehicles-shipped-to-china>.

Fig. 4. Equilibrium quantity and price when $\alpha = 0.4$, $\sigma = 0.7$, $c_H = 0.37$ and $c_L = 0.1$.

Fig. 5. Equilibrium market size and share related to quantity when $\alpha = 0.4$, $\sigma = 0.7$, $c_H = 0.37$ and $c_L = 0.1$.

on Redmi 7 of Xiaomi.inc⁵), noting that other values produce similar insights. We also set $\alpha = 0.4$ and $\sigma = 0.7$ initially (the values of α and σ are based on [29]), but consider the effects of varying them towards the end of the section. Intuitively, as confirmed in Fig. 4, a lower remanufacturing cost leads to a lower price of R and a high production quantity (which is in line with the findings of Ferrer and Swaminathan [19,33]). It also leads to reduced prices of L and H, so that those products stay competitive. Most interestingly, just outside the range of c_R where q_R is positive, namely in Region $H\&L^2$, the high-end firm still lowers the price of H to avoid competition.

Fig. 5 illustrates how the market share related to quantity changes with the remanufacturing cost. We find that offering remanufactured product expands the total market size. In particular, when the cost advantage of remanufactured product is large, the low-end firm can gain a significant amount of market share at the expense of the high-end firm. The market extension effect in our study is consistent with that of Atasu et al. [29]. There are values of c_R , though, where the market share of H increases. For those values, remanufacturing is not (much) more profitable than producing L for the low-end firm, and the high-end firm completely avoids (in region $H\&L^2$) competition from remanufacturing cores by reducing the price of H products. This does not imply that the high-end firm is able to generate additional profit. Indeed, as we show next, the high-end firm always suffers from the threat of re-

Fig. 6. Extra profit from remanufacturing when $\alpha = 0.4$, $\sigma = 0.7$, $c_H = 0.37$ and $c_L = 0.1$.

manufacturing unless remanufacturing is very unprofitable for the low-end firm.

Fig. 6 presents the percentage of the profit increase from remanufacturing in comparison of the benchmark model without remanufacturing. We define this percentage as

$$\frac{\pi_R - \pi_{NR}}{\pi_{NR}} \times 100\%,$$

where π_R stands for the optimal profit under remanufacturing scenario and π_{NR} denotes the optimal profit under no remanufactur-

⁵ <https://item.mi.com/product/10000138.html>.

Fig. 7. Extra profit from remanufacturing when $c_H = 0.37$, $c_R = 0.2$ and $c_L = 0.1$.

ing scenario. We observe from Fig. 6 that there is quite a large range of c_R values where producing R is economical for the low-end firm, but their total profit is still reduced. This is related to the before discussed competitive behaviour of the high-end firm, which reacts to (the threat of) remanufacturing cores entering the market by lowering its price of H products. Ferguson and Toktay [10], Debo et al. [20] also show that cost advantage of remanufacturing is a critical factor for OEMs in deciding whether or not to adopt remanufacturing.

In Fig. 7, we explore the moderating effect of the brand power of R and L as measured by σ and α , respectively. Fig. 7(a) shows that an increase of the brand power of R (through an increased value of σ) can enlarge the profit gained from remanufacturing. However, part (b) of Fig. 7 shows that the increase of the brand power of L reduces the additional profit from remanufacturing. The reason is that the internal competition between R and L then increases, and so remanufacturing high-end products becomes less effective as a diversification strategy. Meanwhile, the high-end firm always suffers from a profit loss caused by remanufacturing due to more intensive competition in the market compared with the scenario without remanufacturing.

Finally, we investigate who benefits from remanufacturing, considering both firms but also consumers and the society as a whole. Thus, we examine the impact of remanufacturing on consumer surplus (CS), social surplus (SS), and absolute profits (AP). The consumer surplus is given by

$$CS = \int_{\frac{p_L - p_R}{\alpha}}^{\frac{p_R - p_L}{\sigma - \alpha}} (\alpha\theta - p_L) d\theta + \int_{\frac{p_R - p_L}{\sigma - \alpha}}^{\frac{p_H - p_R}{1 - \sigma}} (\sigma\theta - p_R) d\theta + \int_{\frac{p_L - p_R}{\alpha}}^1 (\theta - p_H) d\theta, \quad (4)$$

where the first term is the surplus from product L, the second term is the surplus from product R, and the last term is the surplus from product H. The absolute profit is the sum of the high-end firm's profit and the low-end firm's profit. The social surplus is the sum of the consumer surplus and the absolute profit.

Fig. 8 shows that remanufacturing increases both the customer surplus and the social welfare, but decreases the absolute profits in most scenarios ($H, R\&L$ and $H\&L^2$). The absolute profit only increases when the cost advantage is extremely high in the $H\&R$ scenario. Therefore, the remanufacturing strategy benefits customers more than the firms, and the additional surplus of remanufacturing results in the increase of the total social welfare. Therefore, it is valuable for policy makers to promote remanufacturing.

Fig. 8. Additional absolute profits, customer surplus and social welfare from remanufacturing ($\sigma = 0.7$, $\alpha = 0.4$, $c_H = 0.37$ and $c_L = 0.1$).

Next, since Ferguson and Toktay [10] is closely related to our model, we comprehensively compare our results with theirs in order to show the novel insights. We will discuss the differences (indicated by Δp , Δq , and $\Delta\pi$) in prices, quantities and products. For example, Δp_H denotes the price difference of the high-end firm between our model and Ferguson and Toktay [10]. Before presenting the numerical experiments, we highlight the main differences from their model. First, besides remanufactured products, we allow the low-end firm to also produce new products. Second, the high-end firm in our setting is the leader in a Stackelberg game, whereas Ferguson and Toktay [10] consider a Nash game. Then, we calculate the difference between our setting and Ferguson and Toktay [10] with respect to price, quantity, and profit.

Fig. 9 reveals differences in prices and quantities. The prices of R and H in our setting are lower than those in [10]. The reason is that adding L into the low-end firm's product line brings additional competition to R and H. If the remanufacturing cost is relatively low, then the comparative price reduction leads to increased sales of remanufactured products. However, if remanufacturing is costly and so the competition from L more fierce, then fewer products are remanufactured for our setting.

Fig. 9. Optimal strategies for our setting compared with those of [10].

Fig. 10. Profit for our setting compared with that of [10].

Fig. 11. Extra profit compared with only low-end firm remanufacturing.

Fig. 10 presents the profit difference compared to Ferguson and Toktay [10]. We find that both the high-end firm and the low-end firm in our setting gain less profit compared with Ferguson and Toktay [10] due to the increased competition of H, R, and L. However, the gap narrows when the cost advantage of R decreases.

7. Extension: high-end firm also remanufactures

In this section, we explore whether it is profitable for the high-end firm to also perform remanufacturing in order to deter competition. Thus, the high-end firm sells both new and remanufactured products. As before, the high-end firm and the low-end firm engage in Stackelberg competition. We assume that a remanufactured high-end product is valued at a fixed fraction of a new high-end product H, in line with [30].

By performing a similar analysis as that in Section 5, we can obtain the optimal policy for both the low-end firm and the high-end firm. For the sake of brevity and to avoid repetition, we numerically show the impact of the high-end firm by adopting remanufacturing strategy for as c_R increases in Fig. 11. We set $\sigma = 0.7$, $\alpha = 0.4$, $c_H = 0.37$, $c_L = 0.1$, and the customer value for a remanufactured high-end product as 0.8, and unit cost of a remanufactured high-end product as 0.2. We refer to the remanufactured high-end product as RH in this figure.

Fig. 11 presents the profit increase from both firms remanufacturing in comparison of the scenario with only low-end firm remanufacturing. We define this percentage as

$$\frac{\pi_R^B - \pi_R^L}{\pi_R^L} \times 100\%,$$

where π_R^B stands for the optimal profit when both firms consider remanufacturing and π_R^L denotes the optimal profit when only the low-end firm does so. We observe that the low-end firm always faces reduced profits due to the increased competition. By adopting a remanufacturing strategy, the high-end firm can gain extra profit when the remanufacturing cost of the low-end firm is sufficiently high.

8. Conclusions

We investigate the question of when and how a low-end OEM can benefit from collecting and remanufacturing (previous versions of) used high-end products. We derive the equilibrium strategies of both firms in situations with and without a remanufacturing options, providing insights into the effect of such an option on the competitive behavior and resulting prices, quantities, market shares, and profits.

As expected, our results show that the low-end firm can indeed gain extra profit from remanufacturing at the expense of the high-

end firm if cores are not costly to collect and remanufacture. Similar to the study of the profitability condition for remanufacturing (e.g., [10,20]), OEMs adopt the remanufacturing strategy when the unit cost of remanufactured product is below a threshold. For the parameter values by Geyer and Blass [37], that threshold equals \$16.4. As Geyer and Blass [37] note, the average cost to collection and remanufacturing cell phones is \$9.8. Therefore, we conjecture that remanufacturing is profitable in most real-life cases.

The profitability of remanufacturing is moderated by brand power, and highest for a low-end firm when its own product has very low brand power compared to that of a remanufactured high-end product. More interestingly, though, there are many settings where the low-end firm sees its profits reduced, even if remanufacturing is economically viable, due to the fact that the high-end firm protects its market share by lowering its price. From a strategic perspective, this implies that a low-end firm should do a careful market analysis, before announcing publicly that it is considering to engage in remanufacturing high-end products.

Further, due to the fact that the high-end firm lowers its price, the market size of the high-end firm increases in some cases, which in turn increases the availability of cores. As a results, the total market size increases. While both firms may not benefit from remanufacturing, our results show that society as a whole does benefit, which suggests that policy makers should consider providing subsidies to firms in order to promote remanufacturing.

A number of limitations of our work should be mentioned, linking to future research avenues. First, we considered the setting where the high-end firm remanufactures products either to gain additional profit or driven by the take-back regulation. OEMs may also choose to recycle used products instead of remanufacturing them, thereby avoiding cannibalization of new product sales and also limiting the availability to low-end firms and/or independent operators. Future research could incorporate competition for cores into the analysis, although such settings may not be tractable analytically. A second limitation of our work is that it only considers a single period, which can be interpreted as the life cycle of the latest version of a product. This is related to the first discussed limitation in the sense that we assumed an ample supply of used older versions of the high-end product to be available for remanufacturing, avoiding the need to model the timing and production quantities of product versions over time. Future research on multi-period models could link the availability of cores to historical sales. A third limitation of this research is that it only considers two competing OEMs, one low-end firm and one high-end firm. In many real life situations, more than two OEMs compete in the same market. Moreover, beside these OEMs, independent operators may also be interested in obtaining cores, either for remanufacturing/recycling activities or as core brokers. So, where this study considered a single echelon supply chain with two OEMs, future research could analyze a more complex multi-echelon supply chain consisting of OEMs, service providers, and third party collectors.

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Appendix A. Proof of demand function

As stated in [Section 3](#), customers' willingness-to-pay (valuation) θ is uniformly distributed in the interval $[0,1]$ and α and σ are customer's valuation discount to L and R product, respectively. With

normalized market size equal to 1, we can derive the demand function by maximizing customer's utility function.

A1. Proof of Lemma 1

For the scenario without remanufacturing, customers have three choices: buy product H; buy product L; do not buy at all. For a customer to purchase product H, we require that $U^H > U^L$ ($\theta - p_H > \alpha\theta - p_L$) and $U^H > 0$ ($\theta - p_H > 0$), which implies $\theta > \frac{p_H - p_L}{1 - \alpha}$ and $\theta > p_H$. For a customer to purchase product L, we require that $U^L = \theta - p_L > 0$ and $U^H < U^L$ ($\theta - p_H < \alpha\theta - p_L$), which implies $\theta < \frac{p_H - p_L}{1 - \alpha}$ and $\theta > \frac{p_L}{\alpha}$. Therefore, when the customers' utility lies in the interval $[\max\{\frac{p_H - p_L}{1 - \alpha}, p_H\}, 1]$, they purchase H. When the utility lies in the interval $[\frac{p_L}{\alpha}, \frac{p_H - p_L}{1 - \alpha}]$, they purchase L. Based on the analysis of the existence of these two intervals, we obtain two cases: (i) when $p_H < \frac{p_L}{\alpha}$, only H is in the market, and $q_H = 1 - p_H$; (ii) when $p_H \geq \frac{p_L}{\alpha}$, both H and L are in the market, and $q_H = 1 - \frac{p_H - p_L}{1 - \alpha}$ and $q_L = \frac{p_H - p_L}{1 - \alpha} - \frac{p_L}{\alpha}$.

A2. Proof of Lemma 2

For the scenario with remanufacturing, customers have four choices: buy H; buy R; buy L; do not buy at all. For a customer to purchase H, we require that $U^H > U^L$ ($\theta - p_H > \alpha\theta - p_L$), $U^H > U^R$ ($\theta - p_H > \sigma\theta - p_R$) and $U^H > 0$ ($\theta - p_H > 0$), which implies $\theta > \frac{p_H - p_L}{1 - \alpha}$, $\theta > \frac{p_H - p_R}{1 - \sigma}$ and $\theta > p_H$. For a customer to purchase R, we require that $U^R > \max\{U^H, U^L\}$ and $U^R > 0$, which implies $\theta < \frac{p_H - p_R}{1 - \sigma}$, $\theta > \frac{p_R - p_L}{\sigma - \alpha}$ and $\theta > \frac{p_R}{\sigma}$. For a customer to purchase L, we require that $U^L > \max\{U^H, U^R\}$ and $U^L > 0$, which implies $\theta < \frac{p_H - p_L}{1 - \alpha}$, $\theta < \frac{p_R - p_L}{\sigma - \alpha}$ and $\theta > \frac{p_L}{\alpha}$. Therefore, when customer's utility lies in the following three intervals: $[\max\{\frac{p_H - p_L}{1 - \alpha}, \frac{p_H - p_R}{1 - \sigma}, p_H\}, 1]$, $[\max\{\frac{p_R - p_L}{\sigma - \alpha}, \frac{p_R}{\sigma}\}, \frac{p_H - p_R}{1 - \sigma}]$ and $[\frac{p_L}{\alpha}, \min\{\frac{p_H - p_L}{1 - \alpha}, \frac{p_R - p_L}{\sigma - \alpha}\}]$, they purchase H, R and L, respectively. The existence of the intervals decides the market composition, which yields the following four cases.

For $p_H < p_R/\sigma$ and $p_H < p_L/\alpha$, the conditions for purchasing R and L cannot be satisfied for any customer, i.e. for any customer utility between 0 and 1. Thus, only H is in the market and $q_H = 1 - p_H$.

For $\frac{p_L}{\alpha} < p_H < \frac{(1 - \alpha)p_R - (1 - \sigma)p_L}{\sigma - \alpha}$, the condition for purchasing R cannot be satisfied. There are H and L in the market. We have $q_H = \frac{1 - \alpha - p_H + p_L}{1 - \alpha}$ and $q_L = \frac{\alpha p_H - p_L}{\alpha(1 - \alpha)}$.

For $p_R < \frac{\sigma p_L}{\alpha}$, $\frac{p_R}{\sigma} < p_H$, the condition for purchasing L cannot be satisfied. There are H and R in the market. We have $q_H = \frac{1 - \sigma - p_H + p_R}{1 - \sigma}$ and $q_R = \frac{\sigma p_H - p_R}{\sigma(1 - \sigma)}$.

For $p_R > \frac{\sigma p_L}{\alpha}$ and $\frac{(1 - \alpha)p_R - (1 - \sigma)p_L}{\sigma - \alpha} < p_H$, the condition for purchasing H, R, and L always hold. We have $q_H = \frac{1 - \sigma - p_H + p_R}{1 - \sigma}$, $q_R = \frac{p_H - p_R}{1 - \sigma} - \frac{p_R - p_L}{\sigma - \alpha}$, and $q_L = \frac{\alpha p_H - \sigma p_L}{\alpha(\sigma - \alpha)}$.

Appendix B. Proof of Proposition 3

To characterize the optimal response of the low-end firm, we firstly find an analytical expression for the local optimal solution of π_L in each part without considering the corresponding feasibility constraints (ensuring that the solution lies within the considered part of the domain). Then, we obtain the global optimum by incorporating the constraints.

Case 1: $\frac{p_L}{\alpha} < p_H < \frac{(1 - \alpha)p_R - (1 - \sigma)p_L}{\sigma - \alpha}$. By using (1) and Lemma 2, the profit function is given by

$$\pi_L(p_L) = \frac{\alpha p_H - p_L}{\alpha(1 - \alpha)}(p_L - c_L).$$

It is clear that $\pi_L(p_L)$ is concave in p_L . The local optimum is given by

$$\begin{aligned} p_L(H\&L) &= \frac{\alpha p_H + c_L}{2}, \\ q_L(H\&L) &= \frac{\alpha p_H - c_L}{2\alpha(1-\alpha)}, \\ \pi_L(H\&L) &= \frac{(\alpha p_H - c_L)^2}{4\alpha(1-\alpha)}. \end{aligned}$$

To ensure the above solutions in the feasible region, we examine the constraint $\frac{p_L}{\alpha} < p_H < \frac{(1-\alpha)p_R - (1-\sigma)p_L}{\sigma - \alpha}$ with respect to p_L . Substituting $p_L(H\&L)$ into this inequality, we require $p_H > \frac{c_L}{\alpha}$ and $p_R > \frac{(2\sigma - \alpha - \alpha)p_H + (1-\sigma)c_L}{2(1-\alpha)}$.

Case 2: $p_R < \frac{\sigma p_L}{\alpha}$ and $\frac{p_R}{\sigma} < p_H$. The profit function is given by

$$\pi_L(p_R) = \frac{\sigma p_H - p_R}{\sigma(1-\sigma)}(p_R - c_R).$$

It is clear that $\pi_L(p_R)$ is concave in p_R . The local optimum is given by

$$\begin{aligned} p_R(H\&R) &= \frac{\sigma p_H + c_R}{2}, \\ q_R(H\&R) &= \frac{\sigma p_H - c_R}{2\sigma(1-\sigma)}, \\ \pi_L(H\&R) &= \frac{(\sigma p_H - c_R)^2}{4\sigma(1-\sigma)}. \end{aligned}$$

Similar to Case 1, we examine the constraint $p_R < \frac{\sigma p_L}{\alpha}$ and $\frac{p_R}{\sigma} < p_H$ to ensure the above solution in feasible region. Thus, we require $\frac{c_R}{\sigma} < p_H$ and $p_L > \frac{\alpha(\sigma p_H + c_R)}{2\sigma}$.

Case 3: $p_R > \frac{\sigma p_L}{\alpha}$, $p_H > \frac{(1-\alpha)p_R - (1-\sigma)p_L}{\sigma - \alpha}$. The profit function is given by

$$\pi_L(p_L, p_R) = \frac{\alpha p_R - \sigma p_L}{\alpha(\sigma - \alpha)}(p_L - c_L) + \left(\frac{p_H - p_R}{1-\sigma} - \frac{p_R - p_L}{\sigma - \alpha}\right)(p_R - c_R).$$

By checking the corresponding Hessian matrix, we find that the determinant of the matrix is

$$|H| = \begin{vmatrix} -\frac{2\sigma}{\alpha(\sigma - \alpha)} & \frac{2}{\sigma - \alpha} \\ \frac{2}{\sigma - \alpha} & -\frac{2(1-\alpha)}{(1-\sigma)(\sigma - \alpha)} \end{vmatrix} = \frac{4}{\alpha(1-\sigma)(\sigma - \alpha)} > 0.$$

We also have $\partial^2 \pi_L / \partial p_L^2 < 0$ and $\partial^2 \pi_L / \partial p_R^2 < 0$. Therefore, we conclude that $\pi_L(p_L, p_R)$ is jointly concave in p_L and p_R . The local optimal solution is given by

$$\begin{aligned} p_R(H, R\&L) &= \frac{\sigma p_H + c_R}{2}, \\ p_L(H, R\&L) &= \frac{\alpha p_H + c_L}{2}, \\ q_R(H, R\&L) &= \frac{(\sigma - \alpha)p_H - (1-\alpha)c_R + (1-\sigma)c_L}{2(1-\sigma)(\sigma - \alpha)}, \\ q_L(H, R\&L) &= \frac{\alpha c_R - \sigma c_L}{2\alpha(\sigma - \alpha)}, \\ \pi_L(H, R\&L) &= \frac{(\alpha p - c_L)(\alpha c_R - \sigma c_L)}{4\alpha(\sigma - \alpha)} \\ &\quad + \frac{(\sigma p_H - c_R)[(\sigma - \alpha)p_H - (1-\alpha)c_R + (1-\sigma)c_L]}{4(1-\sigma)(\sigma - \alpha)}. \end{aligned}$$

By substituting the local optimum into the corresponding constraint, we have $p_H > \frac{(1-\alpha)c_R - (1-\sigma)c_L}{\sigma - \alpha}$ and $c_L < \frac{\alpha c_R}{\sigma}$.

To obtain the global optimum, we have to compare the profits of these three cases (and opt to exit the market if all are negative), which yields the results of Proposition 3.

Appendix C. Analysis of equilibrium

Based on Eq. (3), the profit function of the high-end firm consists of three cases based on the optimal response of the low-end

firm: (1) only H, (2) both H&L, (3) H&R or H,R&L. The third case combines both H&R and H,R&L since their demand functions are the same. Following a similar logic as for deriving the optimal response of the low-end firm in Appendix B, we firstly determine the local optimum to each case, and then characterize the global optimum by comparing the local optimums and considering the corresponding boundary conditions. The comparison results in seven cases in Figure 1 that characterize the optimal policy of the low-end firm and the high-end firm. The detailed procedure is given as follows.

Case 1: only H.

For this case, the profit function is given by

$$\pi_H(p_H) = (1 - p_H)(p_H - c_H).$$

It is clear that $\pi_H(p_H)$ is concave in p_H and the local optimum is given by

$$\begin{aligned} p_H^*(H) &= \frac{1 + c_H}{2}, \\ q_H^*(H) &= \frac{1 - c_H}{2}, \\ \pi_H^*(H) &= \left[\frac{1 - c_H}{2}\right]^2. \end{aligned}$$

Case 2: both H&L.

For this case, the profit function is given by

$$\pi_H(p_H) = \left[1 - \frac{(2 - \alpha)p_H - c_L}{2(1 - \alpha)}\right](p_H - c_H).$$

It is clear that $\pi_H(p_H)$ is concave in p_H and the local optimum is given by

$$\begin{aligned} p_H^*(H\&L) &= \frac{2(1 - \alpha) + (2 - \alpha)c_H + c_L}{2(2 - \alpha)}, \\ q_H^*(H\&L) &= \frac{2(1 - \alpha) - (2 - \alpha)c_H + c_L}{4(1 - \alpha)}, \\ \pi_H^*(H\&L) &= \frac{[2(1 - \alpha) - (2 - \alpha)c_H + c_L]^2}{8(1 - \alpha)(2 - \alpha)}. \end{aligned}$$

Substituting $p_H^*(H\&L)$ into the best response function of the low-end firm, we obtain

$$\begin{aligned} p_L^*(H\&L) &= \frac{\alpha(2 - \alpha)c_H + (4 - \alpha)c_L + 2\alpha(1 - \alpha)}{4(2 - \alpha)}, \\ q_L^*(H\&L) &= \frac{\alpha(2 - \alpha)c_H - (4 - 3\alpha)c_L + 2\alpha(1 - \alpha)}{4\alpha(1 - \alpha)(2 - \alpha)}, \\ \pi_L^*(H\&L) &= \frac{1}{\alpha(1 - \alpha)} \left[\frac{\alpha(2 - \alpha)c_H - (4 - 3\alpha)c_L + 2\alpha(1 - \alpha)}{4(2 - \alpha)} \right]^2. \end{aligned}$$

Case 3: H&R or H, R&L.

For this case, the profit function is given by

$$\pi_H(p_H) = \left[1 - \frac{(2 - \sigma)p_H - c_R}{2(1 - \sigma)}\right](p_H - c_H).$$

It is clear that $\pi_H(p_H)$ is concave in p_H and the local optimum is given by

$$\begin{aligned} p_H^*(H\&R/H, R\&L) &= \frac{2(1 - \sigma) + (2 - \sigma)c_H + c_R}{2(2 - \sigma)}, \\ q_H^*(H\&R/H, R\&L) &= \frac{2(1 - \sigma) - (2 - \sigma)c_H + c_R}{4(1 - \sigma)}, \\ \pi_H^*(H\&R/H, R\&L) &= \frac{[2(1 - \sigma) - (2 - \sigma)c_H + c_R]^2}{8(1 - \sigma)(2 - \sigma)}. \end{aligned}$$

Substituting p^* into the best response function of the low-end firm, for the scenario of H&R, we obtain

$$p_R^*(H\&R) = \frac{\sigma(2 - \sigma)c_H + (4 - \sigma)c_R + 2\sigma(1 - \sigma)}{4(2 - \sigma)},$$

$$q_R^*(H\&R) = \frac{\sigma(2-\sigma)c_H - (4-3\sigma)c_R + 2\sigma(1-\sigma)}{4\sigma(1-\sigma)(2-\sigma)},$$

$$\pi_R^*(H\&R) = \left[\frac{\sigma(2-\sigma)c_H - (4-3\sigma)c_R + 2\sigma(1-\sigma)}{4(2-\sigma)} \right]^2 \frac{1}{\sigma(1-\sigma)}.$$

Substituting p^* into the best response function of the low-end firm, for the scenario of H,R&L, we obtain

$$p_R^*(H, R\&L) = \frac{\sigma(2-\sigma)c_H + (4-\sigma)c_R + 2\sigma(1-\sigma)}{4(2-\sigma)},$$

$$q_R^*(H, R\&L) = \frac{2(1-\sigma)(\sigma-\alpha) + (2-\sigma)(\sigma-\alpha)c_H + 2(1-\sigma)(2-\sigma)c_L - (4+2\alpha\sigma-3\sigma-3\alpha)c_R}{4(1-\sigma)(\sigma-\alpha)(2-\sigma)},$$

$$p_L^*(H, R\&L) = \frac{2\alpha(1-\sigma) + \alpha(2-\sigma)c_H + \alpha c_R + 2(2-\sigma)c_L}{4(2-\sigma)},$$

$$q_L^*(H, R\&L) = \frac{\alpha c_R - \sigma c_L}{2\alpha(\sigma-\alpha)},$$

$$\begin{aligned} \pi_L^*(H, R\&L) = & \frac{(\alpha c_R - \sigma c_L)(2\alpha(1-\sigma) + \alpha(2-\sigma)c_H + \alpha c_R - 2(2-\sigma)c_L)}{8\alpha(2-\sigma)(\sigma-\alpha)} \\ & + \frac{(\sigma(2-\sigma)c_H - (4-3\sigma)c_R + 2\sigma(1-\sigma))}{16(1-\sigma)(\sigma-\alpha)(2-\sigma)^2} \\ & \times \frac{(2(1-\sigma)(\sigma-\alpha) + (2-\sigma)(\sigma-\alpha)c_H + 2(1-\sigma)(2-\sigma)c_L - (4+2\alpha\sigma-3\sigma-3\alpha)c_R)}{16(1-\sigma)(\sigma-\alpha)(2-\sigma)^2}. \end{aligned}$$

The above analysis yields the local optimum to each case without considering the corresponding boundary conditions. To obtain the global optimum, we have to compare the local optimums of the above three cases and simultaneously consider the corresponding boundary conditions. As the following analysis will show, this implies that several of the above three cases are split into multiple (sub)cases, leading to 7 cases in total with the equilibrium quantities and prices as given in Table 4.

By Proposition 3, when $c_R < \frac{\sigma c_L}{\alpha}$, the low-end firm either only provides R or exits the market. The low-end firm only provides R for $p_H \in [\frac{c_R}{\sigma}, 1]$ and exits the market for $p_H \in [0, \frac{c_R}{\sigma}]$. For the high-end firm, by comparing the local optimums of Cases 1 and 3, we have $\pi_H^*(H\&R) < \pi_H^*(H)$ and $p_H^*(H\&R) < p_H^*(H)$. We have to check whether $p_H^*(H)$ and $p_H^*(H\&R)$ are feasible to achieve the corresponding maximal profits. Then, we obtain the following three cases.

- For $p_H^*(H) < \frac{c_R}{\sigma}$, based on the expression of $p_H^*(H)$ in Case 1, we obtain the condition, i.e., $c_R > \frac{\sigma(c_H+1)}{2}$. We obtain that $p_H^*(H)$ is feasible for $p_H \in [0, \frac{c_R}{\sigma}]$. While, $p_H^*(H\&R)$ is infeasible since $p_H^*(H\&R)$ is not in the interval $[\frac{c_R}{\sigma}, 1]$. Due to the concavity, the profit function of the high-end firm is decreasing in $p_H \in [\frac{c_R}{\sigma}, 1]$. Thus, the global optimal price is given by $p_H^*(H)$ for Case H¹.
- For $p_H^*(H\&R) < \frac{c_R}{\sigma} \leq p_H^*(H)$, we obtain

$$\frac{\sigma(2-\sigma)c_H + 2\sigma(1-\sigma)}{4-3\sigma} < c_R \leq \frac{\sigma(c_H+1)}{2}.$$

For this case, neither $p_H^*(H\&R)$ or $p_H^*(H)$ is feasible. Due to the concavity, the profit function of the high-end firm increases in $p_H \in [0, \frac{c_R}{\sigma}]$ and decreases in $p_H \in [\frac{c_R}{\sigma}, 1]$. So the optimal price is located at the boundary, i.e., $\frac{c_R}{\sigma}$, for Case H².

- For $p_H^*(H\&R) \geq \frac{c_R}{\sigma}$, we obtain $c_R \leq \frac{\sigma(2-\sigma)c_H + 2\sigma(1-\sigma)}{4-3\sigma}$. Only $p_H^*(H\&R)$ is feasible for $p_H \in [\frac{c_R}{\sigma}, 1]$. The profit function of the high-end firm increases in $p_H \in [0, \frac{c_R}{\sigma}]$. So the global optimal price is $p_H^*(H\&R)$ for Case H&R.

By Proposition 3, when $c_R > \frac{\sigma c_L}{\alpha}$, the low-end firm either provides L, or provides both R and L, or exits the market. The low-end firm provides both R and L for $p_H \in [\frac{(1-\alpha)c_R - (1-\sigma)c_L}{\sigma-\alpha}, 1]$, only provides L for $p_H \in [\frac{c_L}{\alpha}, \frac{(1-\alpha)c_R - (1-\sigma)c_L}{\sigma-\alpha}]$, and exits the market for $p_H \in [0, \frac{c_L}{\alpha}]$. For the high-end firm, by comparing the local optimums of Cases 1, 2, and 3, we have $\pi_H^*(H, R\&L) < \pi_H^*(H\&L) < \pi_H^*(H)$ and $p_H^*(H, R\&L) < p_H^*(H\&L) < p_H^*(H)$. We have to check whether these local optimums are feasible. Then, we obtain the following cases.

- For $p_H^*(H) < \frac{c_L}{\alpha}$, we obtain $c_L > \frac{\alpha(c_H+1)}{2}$. Only $p_H^*(H)$ is feasible in $p_H \in [0, \frac{c_L}{\alpha}]$. Due to the concavity, the profit function of high-end firm decreases in $p_H \in [\frac{c_L}{\alpha}, 1]$. So the optimal price is $p_H^*(H)$ for Case H¹.
- For $p_H^*(H\&L) < \frac{c_L}{\alpha} \leq p_H^*(H)$, we obtain

$$\frac{\alpha(2-\alpha)c_H + 2\alpha(1-\alpha)}{4-3\alpha} < c_L \leq \frac{\alpha(c_H+1)}{2}.$$

None of these local optimum is feasible. Due to the concavity, the profit function of the high-end firm increases in $p_H \in [0, \frac{c_L}{\alpha}]$ and decreases in $p_H \in [\frac{c_L}{\alpha}, 1]$. Therefore, the optimal price is located at the boundary, i.e., $\frac{c_L}{\alpha}$ for Case H³.

- For $\frac{c_L}{\alpha} \leq p_H^*(H\&L) < \frac{(1-\alpha)c_R - (1-\sigma)c_L}{\sigma-\alpha}$, we obtain
- $$c_R > \frac{(2-\alpha)(\sigma-\alpha)c_H + (4+2\alpha\sigma-3\alpha-3\sigma)c_L + 2(1-\alpha)(\sigma-\alpha)}{2(1-\alpha)(2-\alpha)}$$
- and $c_L \leq \frac{\alpha(2-\alpha)c_H + 2\alpha(1-\alpha)}{4-3\alpha}$. Only $p_H^*(H\&L)$ is feasible in $p_H \in [\frac{c_L}{\alpha}, \frac{(1-\alpha)c_R - (1-\sigma)c_L}{\sigma-\alpha}]$. The profit function of the high-end firm increases in $p_H \in [0, \frac{c_L}{\alpha}]$ and decreases in $p_H \in [\frac{(1-\alpha)c_R - (1-\sigma)c_L}{\sigma-\alpha}, 1]$. Therefore, the global optimal price is $p_H^*(H\&L)$ for Case H&L¹.
- For $\frac{(1-\alpha)c_R - (1-\sigma)c_L}{\sigma-\alpha} < p_H^*(H\&L)$ and $p_H^*(H, R\&L) < \frac{(1-\alpha)c_R - (1-\sigma)c_L}{\sigma-\alpha}$, we obtain

$$\begin{aligned} \frac{(2-\sigma)(\sigma-\alpha)c_H + 2(1-\sigma)(2-\sigma)c_L + 2(1-\sigma)(\sigma-\alpha)}{4+2\alpha\sigma-3\alpha-3\sigma} & < c_R, \\ \frac{(2-\alpha)(\sigma-\alpha)c_H + (4+2\alpha\sigma-3\alpha-3\sigma)c_L + 2(1-\alpha)(\sigma-\alpha)}{2(1-\alpha)(2-\alpha)} & > c_R. \end{aligned}$$

None of the local optimums is feasible. Due to the concavity, the profit function of the high-end firm increases in $p_H \in [0, \frac{(1-\alpha)c_R - (1-\sigma)c_L}{\sigma-\alpha}]$ and decreases in $p_H \in [\frac{(1-\alpha)c_R - (1-\sigma)c_L}{\sigma-\alpha}, 1]$. Therefore, the optimal price is $\frac{(1-\alpha)c_R - (1-\sigma)c_L}{\sigma-\alpha}$ for Case H&L².

- For $p_H^*(H, R\&L) \geq \frac{(1-\alpha)c_R - (1-\sigma)c_L}{\sigma-\alpha}$, we obtain
- $$c_R \leq \frac{(2-\sigma)(\sigma-\alpha)c_H + 2(1-\sigma)(2-\sigma)c_L + 2(1-\sigma)(\sigma-\alpha)}{4+2\alpha\sigma-3\alpha-3\sigma}.$$

Only $p_H^*(H, R\&L)$ is feasible in $[\frac{(1-\alpha)c_R - (1-\sigma)c_L}{\sigma-\alpha}, 1]$. The profit function of the high-end firm increases in $p_H \in [0, \frac{(1-\alpha)c_R - (1-\sigma)c_L}{\sigma-\alpha}]$. Therefore, the global optimal price is $p_H^*(H, R\&L)$ for Case H, R&L.

In summary, we obtain seven different cases given in Table 4.

Supplementary material

Supplementary material associated with this article can be found, in the online version, at doi:[10.1016/j.omega.2019.102168](https://doi.org/10.1016/j.omega.2019.102168).

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