Impact of intercompetitor licensing on remanufacturing market competition and cooperation

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Abstract

This research investigates the impact of intercompetitor licensing between an original equipment manufacturer (OEM) and an independent remanufacturer (IR) on (1) market competition between new and remanufactured products, (2) the IR's remanufacturing strategy, and (3) the IR's optimal quality choice for remanufactured products. In the considered supply chain, the OEM sells new products, and the IR collects used products and then sells remanufactured products to compete with the OEM. To produce remanufactured products, the IR can acquire remanufacturing technology either by paying a licensing fee to the OEM or self-developing it in-house by incurring a fixed research and development cost. We develop game-theoretic models to determine the optimal supply chain decisions concerning the royalty licensing fee, IR's remanufacturing strategy and production quality, and product sale prices. We find that a licensing contract will always induce the OEM and the IR to increase their sales price for new and remanufactured products. However, the OEM will always increase the sales price for new products to a larger degree than that of the IR. This can alleviate price competition between new and remanufactured products and make remanufactured products more competitive in the market. Under licensing cooperation, the IR will always remanufacture used products to a higher quality level which will intensify quality competition. No matter whether the royalty fee is exogenously or endogenously determined by the OEM, there exists a wide range of parameter regions such that a licensing contract will produce a win-win solution for the OEM and the IR. A licensing cooperation may be reached even when the unit royalty fee is at a relatively low level and the total royalty fee is higher than the self-development option.

Managerial relevance statement: From a practical perspective, this study proposes how the OEM, and the IR should make licensing cooperation decision which aims to achieve a win-win solution. It also reveals that a royalty licensing contract can be mutually acceptable between the OEM and the IR in a wide range of parameter regions. This result is important for managers who want to engage in the

remanufacturing business. For the OEM, the result shows that licensing its remanufacturing technology at a low royalty fee may still be beneficial. For the IR, the result shows that seeking technology licensing may be more profitable even when the total paid royalty fee is higher than the cost of self-developing the technology. Strategic implications of royalty licensing on market competition, remanufacturing production strategy, and remanufacturing quality strategy should be carefully considered before making strategic decisions on remanufacturing and licensing cooperation.

Key words: Intercompetitior licensing; pricing decision; product quality; royalty licensing contract; cannibalize.

1. Introduction

Remanufacturing has become a noteworthy and fast-flourishing industry that can deliver all-round social benefits because it restores a formerly sold, worn, or non-functional product or module to a "like-new" or even "better-than-new" condition [1-5]. In an early report conducted by the U.S. International Trade Commission, it is suggested that the value of the U.S. remanufacturing industry has reached at least $ 43.0 billion, supporting more than 180,000 full-time jobs [6]. Until 2015, the total production value of the European Union remanufacturing industry has reached £ 29.8 billion and supported 192,000 full time jobs [7], and it is estimated that those numbers may reach £ 70 billion and 500,000 by 2030, respectively [8]. Despite the abundant benefits and market scale, many original equipment manufacturers (OEMs) are still reluctant to enter the remanufacturing market which is dominated by independent remanufacturers (IRs) whose core business is to remanufacture used products and sell these remanufactured products to the market [1, 9]. For instance, Hauser and Lund [10] find that only 6% of over 2000 remanufacturing firms are OEMs. A more common industry practice for the remanufacturing industry is that many OEMs cooperate with the IRs through a license agreement [11-14].

Licensing cooperation between an OEM and an IR is a double-edged sword for both parties. From the perspective of the OEM, licensing cooperation with an IR allows the OEM to reach out to low-end customers who could not purchase new products and thus benefit from the development of remanufacturing business. At the same time, new and remanufactured products are offered at different channels since in the licensing cooperation scenario, remanufacturing is conducted independently by the IR. It is widely acknowledged that remanufactured products will cannibalize customers' demand for new products if both products compete in the same market [1-3, 5, 15-21], and the cannibalization effect between new and remanufactured products is a major barrier preventing OEMs from entering the remanufacturing market. For instance, Dell, famous for its direct sales of new products, has experienced a transition from internal remanufacturing to outsourced IR remanufacturing to avoid channel conflict between new and remanufactured products [5, 22]. However, cannibalization still exists and the sales of new products will be affected by the existence of remanufactured products even though they are not offered in the same channel. Therefore, the critical trade-off for the OEM is that whether the indirect benefit from licensing cooperation outweigh the potential negative effect of the loss of new product sales.

From the perspective of the IR, it can obtain technology support from the OEM through licensing cooperation. As a result, the IR does not need to incur fixed cost to self-develop remanufacturing technology as royalty fee paid to the OEM already acts as payoffs of the IR to use the OEM's technology. This allows the IR to focus on remanufacturing and marketing remanufactured products. At the same time, the IR can provide remanufactured products in an excellent condition. For instance, for authorized remanufactured products, eBay highlights on its website, "… have been inspected, cleaned, and repaired to meet manufacturer specifications and is in excellent condition" [23]. However, industry practice for an IR's licensing cooperation decision is diverse. In the China market, Aihuishou and Ifengpai are both specialized IRs that offer remanufactured iPhone to the market. Ifengpai has been authorized by Apple for remanufacturing iPhones, whereas Aihuishou is still not authorized by Apple and engages in remanufacturing Apple's products independently [13]. In other words, Apple will provide all the necessary technology and know-how to Ifengpai so that it does not need to self-develop remanufacturing technology to remanufacture used products. However, for the other IR, Aihuishou, it does not seek for a license cooperation with the OEM and chooses to develop remanufacturing technology in-house. The critical trade-off for the IR is that whether the direct benefit from technology licensing can outweigh the fixed cost incurred for self-developing technology. In addition, some IRs choose to remanufacture used products at different quality levels so that they can better satisfy the needs of different customers [3, 24]. For instance, for refurbished forklift trucks, Linde offers three standards of refurbished products [8]. This practice can help IR better segment and service customers but surely complicate licensing cooperation decision between the OEM and the IR.

Designing a win-win licensing cooperation agreement between an OEM and an IR is challenging and there is little guidance for managers as the industry practice is diverse. In this paper, we address the following research questions aiming to help OEMs and IRs who may face similar challenges:

(1) What is the OEM's and IR's optimal responses when the IR can remanufacture used products by either self-developing the remanufacturing technology or obtaining licensing from the OEM?

(2) Should the IR obtain remanufacturing technology license from the OEM even if it can develop it in-house? Should the OEM interfere with the remanufacturing market by signing a license agreement with the IR who offers the remanufactured version of its product to the market?

(3) What is the impact of remanufacturing technology license on market equilibrium and the IR's optimal quality choice of remanufactured products?

To address the above questions, we consider a game-theoretic model in which the OEM and the IR simultaneously and respectively sell new and remanufactured products to the market. Customers are heterogenous regarding their willingness to pay for product quality. The IR has two options to obtain the remanufacturing technology to produce remanufactured products. One is to self-develop the technology by incurring a fixed research-and-development (R&D) cost, and the other is to license it from the OEM by paying the OEM royalty fee. We assume that the IR can choose between two quality levels for the remanufactured products denoting a high-quality production strategy and a low-quality production strategy to be consistent with real-world applications. The aim of this assumption is to ensure obtaining analytical closed-form solutions. In addition to determining the quality of remanufactured products, the IR also needs to decide the number of units to be collected and remanufactured. After that, the OEM and the IR will simultaneously set sales price for new and remanufactured products to compete in the same market. In the subsequent analysis, the main findings remain qualitatively the same when the licensing can increase customers' willingness to pay for remanufactured products, when the quality of remanufactured products is a continuous decision variable, and when the OEM determines the royalty fee after observing the IR's optimal quality choice.

There are three main findings from this research. First, consistent with Jiang and Shi [25], a royalty licensing contract between an OEM and an IR can lead to higher equilibrium sale prices for both firms, while the OEM will always raise its sales price by a larger degree than that of the IR. This will increase the price difference between new and remanufactured products and thus, soften price competition between the two firms. However, the competition between the two firms will be tightened rather than softened. Extant literature finds that intercompetitor licensing whether in both horizontally and vertically differentiated market will lead to higher prices in the market [25-27]. Our research shows that, in the new and remanufactured products coexist context, intercompetitor licensing will still induce firms to increase their sales price and thus alleviate price competition between firms. However, the price competition-alleviating effect will not reduce the competition between the OEM and the IR. This is because both the OEM and the IR will respectively raise their sales price, but the OEM will always raise its sales price by a larger degree. As a result, the competition between the OEM and the IR will tighten, and remanufactured products will become more competitive in the market.

Second, licensing remanufacturing technology will always induce the IR to remanufacture used products at a high-quality level regardless of the IR's production quantity. As such, the quality difference between new and remanufactured products will decrease if the IR adopts the high-quality production strategy, indicating that the royalty licensing contract between the OEM and the IR has a competition-intensifying effect from the product quality perspective. This result is completely different with Jiang and Shi [25]. They show that the intercompetitor licensing between an entrant and an incumbent will induce the entrant to choose two different production strategies which are differentiated by the innovation of the core technology, and the quality competition can either be intensified or alleviated after the cooperation. However, we show that the IR will always choose a high-quality level when there is an intercompetitor licensing contract between the OEM and the IR, leading to a competition-intensifying effect on product quality.

Third, regarding the OEM's attitude towards remanufacturing and remanufacturer by using licensing contract, many researchers had identified the conditions under which the OEM should embrace or deter the entry of the IR, such as Oraiopoulos, et al. [11], Liu, et al. [12], Zhou, et al. [13], and Zhou, et al. [14]. In this research, we also show that a wide range of parameter regions for mutually acceptable licensing contracts exist for the OEM and the IR while considering IR's remanufacturing technology and remanufacturing quality decisions. We find that the OEM can benefit from the royalty licensing contract even when the unit royalty fee paid by the IR is at a relatively low level, and that the royalty licensing contract is beneficial for the IR even when the total royalty fee paid to the OEM is larger than the incurred R&D cost of self-developing the technology. This finding holds regardless of the royalty fee being exogenously or endogenously determined by the OEM. In general, the OEM should not cooperate with the IR when the royalty fee paid by the IR is low as cannibalization exists between new and remanufactured products. However, this result shows that such intuitively sound decision-making is not true. Under a royalty licensing contract, the cannibalization effect still exists and will increase. However, the OEM can benefit from the total licensing fee it collects from the IR and a higher profit margin because of the higher sales price of new products. For the IR, it may still prefer accepting the royalty licensing contract even when the total royalty fee is higher than the alternative R&D cost. This is because, through a licensing cooperation, remanufactured products will become more competitive because of a relatively lower sales price and a higher quality.

The rest of this paper is organized as follows. In Section 2, we briefly review the previous work relates to our topic. Model descriptions and assumptions are presented at Section 3. The benchmark case without licensing is examined at Section 4. Section 5 investigates the OEM's and IR's optimal decisions in the main case with a royalty licensing contract. Several extensions of the main model are discussed at Section 6. Section 7 concludes the paper, and all proofs are provided at the E-Companion.

2. Literature review

This study is built on four streams of research: (a) firm's make-or-buy decision; (b) firm's licensing decision; (c) authorization remanufacturing; and (d) quality innovation.

A firm's make-or-buy (i.e., production outsourcing) decision is a stream of research that has been studied in multiple disciplines by many scholars, for which Tsay [28] can serve as an overview. Our research closely relates to the stream of literature that examines a firm's production outsourcing decision in a competitive setting where both cooperation and competition exist between firms. Chen, et al. [29] examined a larger OEM's component procurement strategy with a contract manufacturer (CM) when it also produces for a smaller OEM. Wang, et al. [30] investigated the impact of game sequence on the OEM's production outsourcing strategy with an CM when the latter can act as both upstream partner and downstream competitor. Niu, et al. [31] studied the presence of a competitive supplier and a non-competitive supplier on the OEM's dual sourcing decision. Niu, et al. [32] investigated the production outsourcing decision of two competitive manufacturers who offer substitutable limited-edition luxury goods to the market with considering customers' origin preferences. Niu and Mu [33] examined an OEM's procurement outsourcing decision with a competitive logistics service provider (LSP) in a supply chain where the OEM and LSP sell substitutable products to the market and the LSP may also put efforts in developing sustainable logistics, and the sustainable service provided by the LSP has the potential to increase the OEM's market demand. We contribute to this stream of literature by examining a firm's production outsourcing decision in a competitive setting, while we extend current research from manufacturing activity to remanufacturing activity which incorporates the special link between new and remanufactured products. Wang, et al. [2] evaluated whether a retailer should remanufacture in-house or outsource considering quality of used products, remanufacturing cost structure, and bargaining power of third-party remanufacturer. They found that the key driver for a profit-maximizing retailer to choose between in-house remanufacturing and outsourcing is differentials in variable remanufacturing cost, and outsourcing dominates in-house remanufacturing when there is a high fixed cost for self-remanufacturing. This literature on firm's make-or-buy decision focuses on physical components or activities of its manufacturing or remanufacturing process. Conversely, we examine whether the OEM should license remanufacturing technology to a competing IR who sells the remanufactured version of its products to the market which will cannibalize customers' demand for new products. The IR, on the other hand, can either accept the royalty licensing contract offered by the OEM or incur a fixed R&D cost to self-develop the technology. Moreover, we evaluate the impact of intercompetitor licensing of remanufacturing technology on the IR's optimal quality choice for remanufactured product in addition to market competition between new and remanufactured products.

Next, the research on firm's licensing decisions is another stream of research that relates to our study. As one of the earliest literature, Tandon [34] examined social and private incentives for licensing and its impact on research activity. Gallini [35] found that licensing of production technology from an incumbent firm may reduce the entrant's incentive in developing its own or possible better technology and thus, deter the entry of the entrant. Hernández-Murillo and Llobet [36] investigated the optimal licensing contract between a licensor and licensees where technology of the licensor has a cost-reducing effect and licensees are heterogenous in new technology use. They found that licensing of technology can not only help the patentholder separate licensees but also soften competition in the downstream market. Kitagawa, et al. [37] investigated the setting of a two-part tariff for an incumbent who licenses technology of new product to a potential entrant. Negoro and Matsubayashi [38] used a game-theoretical approach to examine partner selection strategy of an entrant firm when it wants to offer its new product in a foreign market. The product offered by the entrant has either a brand advantage or technological superiority over incumbent firms, and licensing can act as one less intensive alliance formation for the entrant to choose. The main topic for this broad stream of literature is whether patentholder should license its technology to a potential rival and how. Consistent with this stream of research, we also examine technology licensing decision from the perspectives of the OEM and the IR, and how the royalty contract affect the OEM's and IR's optimal pricing and quality decisions in the market equilibrium.

In particular, Jiang and Shi [25] examined licensing cooperation between an incumbent and an entrant. They also studied the impact of the licensing contract on the entrant's product quality innovation decision in addition to the price competition where the incumbent's technology provides an undifferentiated product. Our work is in line with Jiang and Shi [25] by categorizing licensing cooperation between two competing firms, but is also different in several important aspects. First, we focus on the coexistence of new and remanufactured products, whereas Jiang and Shi [25] examine the technology license of general product, which leads to a different model setting. Second, the number of cores available for remanufacturing is always smaller than the number of cores that can be collected from the market, meaning that customers' demand for remanufactured products is always smaller than that of for new products, whereas general product does not have such constraint. Third, customers' valuation or preference for remanufactured products is always smaller than that of new products though the IR can remanufacture the used products to the same quality level of the new product. This is determined by the characteristic of remanufactured products. Jiang and Shi [25] considered the scenario where the entrant can innovate on the incumbent's product and choose a quality that is higher than the incumbent's product since the licensing cooperation between the incumbent and entrant is on a noncore technology. We contribute to this stream of literature on firm's licensing decision from a general product to the remanufactured product by considering the strategical interaction between new and remanufactured products. Our result suggests that convention wisdom on the strategic adoption of intercompetitor licensing should be applied with caution.

Another related research stream focuses on authorization in remanufacturing. Some products, such as software products, are often not transferrable among hardware results in a relicensing contract where the OEM charges a relicense fee to any customer who purchases refurbished products. Oraiopoulos, et al. [11] examined the OEM's incentives and optimal strategies toward the existence of the secondary market where the OEM can directly influence the secondary market by charging a relicensing fee to the buyers, and identified the conditions under which the OEM should favor or deter the secondary market. Generally, authorization remanufacturing happens between an OEM and an IR where the OEM seeks to embrace the existence of remanufactured products when cannibalization effect arises. Zou, et al. [39] considered that an OEM and an IR cooperate under two remanufacturing modes (i.e., outsourcing and authorization) and then compared the two remanufacturing modes in terms of equilibrium quantities, prices, and profits. Ma, et al. [40] evaluated the conditions under which the OEM and the IR are most likely to cooperate with each other in remanufacturing by comparing unlicensed and licensed remanufacturing scenarios. Liu, et al. [12] differentiated customers' preference among used products refurbished by the OEM, authorized IR, and unauthorized IR. The authors examined the conditions under which refurbishing authorization strategy is an optimal choice for the OEM. Zhou, et al. [13] investigated an OEM's remanufacturing authorization decision when competition exists in the secondary market. Zhou and Yuen [19] examined an OEM's remanufacturing partner selection over two remanufacturing modes: authorization and outsourcing, and identified OEM's and IR's preference over these two modes. Jin, et al. [41] considered dealer authorization mode where an OEM can turn an IR into an authorized seller that sells both new and remanufactured products and found that remanufacturing authorization between an OEM and an IR depends on the improvement of customers' willingness to pay for the remanufactured products because of the authorization cooperation. From the perspective of global supply chains, Guo, et al. [42] investigated how local clothing manufacturing in least developed countries is affected by second-hand clothing imports. We contribute to this stream of literature by also considering an OEM's remanufacturing authorization strategy with an IR which not only models the cannibalization effect between new and remanufactured products but also considers remanufacturing cooperation between an OEM and an IR. However, we focus on investigating the impact of an OEM's remanufacturing technology licensing decision on an IR's optimal quality choice for remanufactured products and market equilibrium.

Our research complements the stream of research on firm's quality innovation decision, especially in the coexistence of new and remanufactured products context. Örsdemir, et al. [43] considered that an OEM uses product quality and quantity as strategic levers against the entry of an IR where the quality of new products is changeable, and found that the OEM relies more on quality decision when it is in a stronger competitive position and more heavily on limiting the quantity of available cores otherwise. Chen and Chen [3] examined refurbishing quality decision of a refurbishing firm where the refurbishing firm can flexibly determine the quality of its refurbished products by considering competition among new, remanufactured, and refurbished products. Shi, et al. [5] examined conflict and coordination between manufacturing and remanufacturing operations by endogenizing product design decision of new products, i.e., whether the firm should design a product to be remanufacturable. However, they focused on coordinating inter-divisional conflicts between a manufacturing division and a remanufacturing division. The role of information sharing on firm's quality innovation decision has also been examined. Hu, et al. [44] studied the impact of a distributor's demand information sharing on game quality investment and found that the sharing of demand information may not necessarily motivate developer to improve product quality. We contribute to this stream of research by endogenizing the quality decision of remanufactured products and by exploring the impact of a royalty licensing contract between an OEM and an IR on market equilibrium. An innovation activity can be performed by focal firm in-house or be outsourced to other supply chain members. Raz, et al. [45] separated innovation into two parts, i.e., process innovation and product innovation. Process innovation is a kind of activity that can result in cost reduction and product innovation is a kind of activity that can increase the quality of the product and result in the increase of customer value. The authors incorporated the two types of innovation into a supply chain and examine the key decisions of the chain's focal firm regarding innovation and whether the focal firm should perform innovation in-house or should it outsource these innovation activities to other supply chain members. From the standpoint of remanufacturing technology, we also consider whether the IR should self-develop it in-house or license it from the OEM and in either scenario, the IR also needs to decide to remanufacture at a suitable quality level since it can incur different remanufacturing cost.

This research contributes to both our understanding of competition and cooperation relations between an OEM and an IR and the impact of the intercompetitor license on IR's remanufacturing quality decision and market equilibrium. Specifically, our contributions include the following.

(1) Studying IR's remanufacturing technology decision, i.e., whether the IR should self-develop the remanufacturing technology in-house by incurring fixed cost or should it license the technology from the OEM by paying royalty fee.

(2) Evaluating the impact of intercompetitor license between an OEM and an IR on IR's remanufacturing quality decision and the subsequent market equilibrium.

(3) Identifying the conditions under which licensing contract is mutually acceptable for an OEM and an IR, i.e., when licensing becomes a win-win solution for both parties.

The position of this research in the literature is summarized in Table 1.

Table 1. Position of this research in the literature (Yes: √; No: ×).

Studies	Production outsourcing		Licensing decision	Remanufacturing authorization	Quality innovation
	Competitive setting	Remanufacturing			
[28-33]	√	×	×	×	×
[2]	√	√	×	×	×
[34-38]	×	×	√	×	×
[11-13, 19, 39-42]	×	×	√	√	×
[3, 5, 43-45]	×	×	×	×	√
[25]	√	×	√	×	√
This study	√	√	√	√	√

3. Model Setting

This paper considers a supply chain consisting of an OEM and an IR that simultaneously and respectively sell the new and remanufactured version of a single type of products to the market. The OEM sells new products with a quality level q_n, and the IR enters the market by collecting and remanufacturing used products and then sells remanufactured products with a quality level q_r. The OEM may refer to manufacturers who offer new forklift trucks, and the IR may refer to Linde Material Handling GmbH who provides remanufactured forklift trucks with different levels of quality standards [8]. Compared with the manufacturing process of new products, the technology needed to remanufacture used products is a noncore technology for the OEM and thus such technology is transferrable since remanufacturing is a process that brings used products to “as-new” or “like-new” condition. Hence, remanufacturing is more likely a process that restores the original functionality of new products [43, 46]. Therefore, the OEM surely has the technology needed to remanufacture used products. However, to produce remanufactured products, the IR needs to obtain remanufacturing technology by either (1) self-developing it in-house or (2) licensing it from the OEM. In the first scenario, the IR incurs a fixed research and development (R&D) cost F. In the second scenario, the OEM provides the remanufacturing technology for remanufacturing used products to a certain quality level and charges the IR a unit royalty fee of r for every unit of remanufactured product sold in the market. This paper refers the former scenario as the benchmark case where there is no license cooperation between the OEM and the IR. The latter scenario is referred to as the main case where the OEM and the IR cooperate through a license agreement in remanufacturing technology.

Corresponding to commonly used dual quality level strategy (i.e., high-quality and low-quality) in real-world situations, this paper assumes that the IR can choose between two quality levels for remanufactured products. The dual-level quality assumption has been widely used in quality innovation literature, such as Jiang and Shi [25], for analytical tractability. In the extension section, the dual-level quality assumption will be relaxed by assuming that the quality level of remanufactured products is a continuous variable to verify the robustness of the main results. Let $q_r \in \{q_r^H, q_r^L\}$ denote the quality level of high and low cases, respectively. The quality levels satisfy $q_n > q_r^H > q_r^L$ as the quality level of remanufactured products being lower than that of new products prevails in practice [3]. Under extreme conditions, remanufactured products may reach the same quality level of new products and this research does not consider these extreme conditions. The marginal cost to produce a new and remanufactured product is c_n and c_r, respectively. Note that $c_n > c_r$ always holds as the remanufacturing process is cost-saving by reusing the used products, components, materials, or modules [5, 47-49]. Let $c_r \in \{c_r^H, c_r^L\}$ represents the associated marginal cost to produce the two quality levels of remanufactured products, where $c_n > c_r^H > c_r^L$. Following [43], [2], [3], and [5], this research also assumes that the marginal remanufacturing cost subsumes the cost of all remanufacturing-related activities, such as collection, transportation, sorting, and so on.

Customers are heterogenous regarding the quality of the product, and θ represents customers' willingness to pay (WTP) for the quality and is uniformly distributed on the interval $[0,1]$. Customers can gain a utility of $u_i = \theta q_i - p_i$ if they purchase a product i at the price p_i with the quality level q_i [3, 43]. Hence, the utility for purchasing a new product is $u_n = \theta q_n - p_n$, and the utility for purchasing a remanufactured product is $u_r = \theta q_r - p_r$. Without loss of generality, the market size is normalized to 1. This research assumes that the outside option for customers is zero, and customers will purchase the product that delivers the highest utility. Each customer will purchase at most one unit of product to satisfy his/her needs. Let D_n and D_r denote customers' demand for new and remanufactured products, respectively. Customers will purchase a new product if and only if $u_n \geq u_r$ and $u_n \geq 0$, and customers will purchase a remanufactured product if and only if $u_r \geq u_n$ and $u_r \geq 0$. Therefore, customers' demand for new and remanufactured products can be obtained as follows:

$$D_n = 1 - \frac{p_n - p_r}{q_n - q_r}$$

$$D_r = \frac{p_n - p_r}{q_n - q_r} - \frac{p_r}{q_r}$$

This study assumes that all events transpire within a single period. The single period assumption prevails in operations research, which helps the analyses focus on the average status of the supply chain when similar products are introduced to the market repeatedly, and is applicable to products, such as components, automobile parts, engines, and so on [2, 3, 5, 19, 47]. In addition, this research assumes that the number of products remanufactured for sale equals the number of products collected from the market by the firm (i.e., all collected products can be remanufactured), but the demand for remanufactured products is always smaller than that of new products, thus, $0 \leq D_r \leq D_n$. This constraint means that the number of products that can be remanufactured is not greater than the number of products that is available for remanufacturing and consistent with studies in the operations literature, such as Wang, et al. [2] and Shi, et al. [5].

This study denotes the IR's remanufacturing strategy as S, where $S \in \{NR, R1, R2\}$. Strategy *NR* means the strategy that the IR does not engage in remanufacturing (i.e., $D_r = 0$), strategy *R1* denotes the strategy that the IR collects and remanufactures some of the used products but not all (i.e., $0 < D_r < D_n$), and strategy *R2* represents the strategy that the IR collects and remanufactures all the used products available for remanufacturing (i.e., $0 < D_r = D_n$). The aim of this study is to investigate the impact of license agreement between the OEM and the IR on the remanufacturing market equilibrium and the IR's optimal quality choice of remanufactured products. Hence, this study does not consider strategy *NR* in this study as there is no remanufacturing in this case.

For the IR, the product development involves decisions on license cooperation (i.e., self-development or gain license) and the quality choice of remanufactured products. As the decision for the quality choice of remanufactured products is more adjustable than the decision on license cooperation, we assume that the IR determines its license cooperation first and then on the quality choice of remanufactured products. The sequence of the multi-stage game between the OEM and the IR is described as follows: First, the OEM decides the unit royalty fee (i.e., r) charged to the IR for using its remanufacturing technology. Second, the IR decides the license cooperation, and thus, determines whether to accept or reject the license cooperation contract. If the IR accepts the contract offered by the OEM, then the IR needs to pay the OEM royalty fee for every unit of remanufactured products sold on the market for using the OEM's technology. If the IR rejects the license cooperation contract, the IR needs to incur a R&D cost F to develop its own remanufacturing technology to engage in remanufacturing. Third, the IR determines the quality choice of remanufactured products (i.e., high-quality or low-quality). Fourth, the OEM and the IR simultaneously and respectively decide the sales price for new and remanufactured products (i.e., p_n and p_r). Finally, customers purchase the product (new or remanufactured one) that can give them the highest utility. The sequence of the game is illustrated in Figure 1.

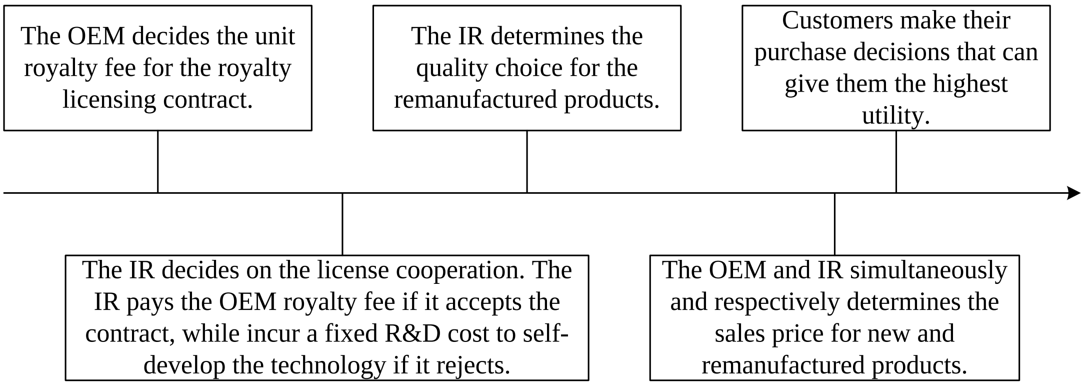

Figure 1. The sequence of the game.

The game can be solved by backward induction. Furthermore, the quality of the new product is normalized to 1 (i.e., $q_n = 1$) as the baseline to investigate the impact of the royalty fee licensing contract on the IR's optimal quality choice.

Let Π_j^k represent player *j*'s profit in case k, where $j \in \{OEM, IR\}$ denotes the two supply chain players (i.e., OEM and IR) and $k \in \{B, M\}$ represents the benchmark case and main case, respectively. All the notations used in this paper are summarized in Table 2.

Table 2. Notations

Symbol	Definition
Model parameters	
θ	Customers' WTP for the quality and is uniformly distributed on the interval $[0,1]$.
u_n	The utility from purchasing a new product.
u_r	The utility from purchasing a remanufactured product.
c_n	The marginal production cost of new products.

c_r	The marginal production cost of remanufactured products, and $c_r \in \{c_r^H, c_r^L\}$ represents the associated marginal cost to produce the two quality levels of remanufactured products.
D_n	Customers' demand for new products.
D_r	Customers' demand for remanufactured products.
F	Fixed R&D cost incurred for self-developing technology.
q_n	Quality level of new products, and is normalized to 1.
Decision variables	
q_r	Quality level of remanufactured products, and $q_r \in \{q_r^H, q_r^L\}$ denotes the quality level of high and low cases, respectively.
p_n	Sales price of new products.
p_r	Sales price of remanufactured products.
r	Unit royalty fee the OEM charges from the IR in licensing cooperation scenario.
Others	
Π_j^k	Player j's profit in case k, where $j \in \{OEM, IR\}$ denotes the two supply chain players (i.e., OEM and IR) and $k \in \{B, M\}$ represents the benchmark case and main case, respectively.
S	Remanufacturing strategy and $S \in \{NR, R1, R2\}$.

4. Benchmark Case without Licensing

This section discusses the benchmark case where there is no license cooperation between the OEM and the IR. The IR engages in remanufacturing by self-developing the remanufacturing technology and incurring a fixed R&D cost. The multi-stage game between the OEM and the IR is solved by backward induction. In the following subsections, Subsection 4.1 first investigates the OEM's and the IR's pricing decisions for new and remanufactured products. Subsection 4.2 then provides the IR's quality decision of remanufactured products.

4.1. Pricing Decisions

The OEM's profit comes from selling new products, and the IR's profit comes from selling remanufactured products minus the R&D cost F. The OEM's and IR's profit functions are:

$$\Pi_{OEM}^B(p_n^B) = (p_n^B - c_n)D_n^B$$

$$\Pi_{IR}^B(q_r^B, p_r^B) = (p_r^B - c_r)D_r^B - F$$

$$\text{s.t. } 0 < D_r^B \le D_n^B$$

We obtain the OEM's and IR's optimal pricing decisions by solving the KKT necessary conditions. The optimal results are summarized in Proposition 1. Subscripts *R1* and *R*2 are added to the optimal solutions to differentiate two remanufacturing strategies. Define $c_{r1}^B = \frac{1}{2}q_r\left(c_n(3-q_r)+q_r-1\right)$ and $c_{r2}^B = \frac{q_r\left(1+c_n-q_r\right)}{2-q_r}$.

Proposition 1. The OEM's and IR's optimal results in the benchmark case without licensing are:

(1) In remanufacturing strategy *R1* where the IR collects and remanufactures some of the used

products but not all, the existence condition for this strategy is: $c_{r1}^{B} < c_r < c_{r2}^{B}$. The optimal pricing decisions for the OEM and the IR are: $p_{n-R1}^{B*} = \frac{2+2c_n + c_r - 2q_r}{4-q_r}$ and $p_{r-R1}^{B*} = \frac{2c_r + q_r(1+c_n - q_r)}{4-q_r}$, and the corresponding profits are: $\prod_{OEM-R1}^{B*} = \frac{\left(2+c_r - c_n(2-q_r) - 2q_r\right)^2}{(4-q_r)^2(1-q_r)}$ and $\prod_{IR-R1}^{B*} = \frac{\left((1+c_n - q_r)q_r - c_r(2-q_r)\right)^2}{(4-q_r)^2(1-q_r)q_r} - F$.

(2) In remanufacturing strategy *R2* where the IR collects and remanufactures all the used products available for remanufacturing, the existence condition for this strategy is: $c_r < c_{r1}^{B}$. The optimal pricing decisions for the OEM and the IR are: $p_{n-R2}^{B*} = \frac{1}{2}\left(1+c_n - (1-c_n)q_r\right)$ and $p_{r-R2}^{B*} = c_n q_r$, and the corresponding profits are: $\prod_{OEM-R2}^{B*} = \frac{1}{4}(1-c_n)^2(1-q_r)$ and $\prod_{IR-R2}^{B*} = \frac{1}{2}(1-c_n)(c_n q_r - c_r) - F$.

Proposition 1 implies that the IR will collect and remanufacture all the used products when the cost of remanufacturing is at a relatively low level (i.e., $c_r < c_{r1}^{B}$). The IR will decrease its collecting and remanufacturing quantity and not collect all the used products when the cost of remanufacturing increases (i.e., $c_{r1}^{B} < c_r < c_{r2}^{B}$). Moreover, the IR will not engage in remanufacturing if the cost of remanufacturing is relatively high (i.e., $c_r > c_{r2}^{B}$). In the two remanufacturing strategies, the IR will offer different sales price for remanufactured products, which will influence the OEM to strategically adjust its pricing strategy for new products. The sales prices for the new and remanufactured products are affected by the production cost of new and remanufactured products and the quality level of remanufactured products. However, it is interesting to note that the production cost of the remanufactured product has no impact on the OEM's and IR's optimal decisions in strategy *R2*. This is because, in strategy *R2*, the production cost of remanufactured products is relatively low, inducing the IR to collect and remanufacture all the used products that are available for collection. In addition, the sales price of new products decreases with the increase of the quality level of remanufactured products, but sales price of remanufactured products increases with the quality level of remanufactured products. This result is intuitive in that remanufactured products will become more competitive when the quality level increases, which can increase customers' WTP for remanufactured products. Besides, the IR must remanufacture used products at a high production cost if it wants to improve the quality level. As such, the IR will transfer the additional cost burden to customers by increasing the sales price of remanufactured products. However, the OEM has to take opposite measures when the quality level of remanufactured products increases.

4.2. IR's Quality Decision

To examine the IR's optimal quality choice for remanufactured products, it is necessary to decide which quality-cost pair yields a higher profit for the IR. Let Π_{IR}^{B-H*} denote the scenario when the quality and production cost of remanufactured products are both at a high level (i.e., $q_r = q_r^H$ and $c_r = c_r^H$), and let Π_{IR}^{B-L*} represent the scenario when the quality and production cost of remanufactured products are both at a low level (i.e., $q_r = q_r^L$ and $c_r = c_r^L$). Hence, in remanufacturing strategy *R1*, the IR's profit is $\Pi_{IR-R1}^{B-H*} = \frac{\left((1+c_n-q_r^H)q_r^H - c_r^H(2-q_r^H)\right)^2}{(4-q_r^H)^2(1-q_r^H)q_r^H} - F$ if it chooses the high-quality production strategy, and the IR's profit is $\Pi_{IR-R1}^{B-L*} = \frac{\left((1+c_n-q_r^L)q_r^L - c_r^L(2-q_r^L)\right)^2}{(4-q_r^L)^2(1-q_r^L)q_r^L} - F$ if it chooses the low-quality production strategy. Similarly, in remanufacturing strategy *R2*, the IR's profit is $\Pi_{IR-R2}^{B-H*} = \frac{1}{2}(1-c_n)(c_n q_r^H - c_r^H) - F$ if it chooses the high-quality production strategy, and the IR's profit is $\Pi_{IR-R2}^{B-L*} = \frac{1}{2}(1-c_n)(c_n q_r^L - c_r^L) - F$ if it chooses the low-quality production strategy. The comparison of the two production strategies under the two remanufacturing strategies is summarized in Lemma 1.

Lemma 1. In the benchmark case without licensing, the IR's optimal quality choice for remanufactured products in the two remanufacturing strategies is:

(1) In remanufacturing strategy *R1*, for any $c_r^H, c_r^L \in \left(c_{r1}^B, c_{r2}^B\right)$, the IR will choose the high-quality production strategy if $c_r^L < c_r^H < c_{r1}$ and the low-quality production strategy otherwise, where $c_{r1} = \frac{q_r^H\left(c_n + (1-q_r^H)\right) - R\left((1+c_n-q_r^L)q_r^L - c_r^L(2-q_r^L)\right)}{(2-q_r^H)}$ and $R = \frac{4-q_r^H}{4-q_r^L}\sqrt{\frac{(1-q_r^H)q_r^H}{(1-q_r^L)q_r^L}}$.

(2) In remanufacturing strategy R2, for any $c_r^H, c_r^L \in \left(0, c_{r1}^B\right)$, the IR will choose the high-quality production strategy if $c_r^L < c_r^H < c_{r2}$ and the low-quality production strategy otherwise, where $c_{r2} = c_r^L + c_n(q_r^H - q_r^L)$.

Lemma 1 provides the IR's optimal quality choice for remanufactured products in the two remanufacturing strategies when the IR engages in remanufacturing by self-developing the remanufacturing technology. It shows that the IR will choose the high-quality production strategy if the production cost of high-quality products is smaller than a threshold. Otherwise, the IR should choose the low-quality production strategy. This result is intuitive. The high-quality production strategy can give the IR a higher profit if it can remanufacture at a low production cost as customers have a high willingness to pay for high-quality products. However, the IR needs to choose the low-quality option if the remanufacturing cost is high.

5. Main Case with Licensing

In the main case, the OEM and the IR cooperate with each other through a license agreement in which the OEM charges the IR a unit of royalty fee r by providing necessary technological assistance to help the IR reach a certain quality level for remanufactured products. In this section, the OEM's and IR's optimal pricing decisions are investigated in Subsection 5.1. The IR's optimal quality choice of remanufactured products is examined in Subsection 5.2. Finally, Subsection 5.3 investigates the OEM's royalty fee decision considering the IR's participation condition.

5.1. Pricing Decisions

In this case, the OEM's profit comes from selling new products and the royalty fee paid by the IR. Similarly, the IR's profit comes from selling remanufactured products minus the royalty fee paid to the OEM. The OEM's and IR's profit functions are:

$$\Pi_{OEM}^{M}(p_n^M, r) = (p_n^M - c_n)D_n^M + rD_r^M$$

$$\Pi_{IR}^{M}(q_r^M, p_r^M) = (p_r^M - c_r)D_r^M - rD_r^M$$

$$\text{s.t. } 0 < D_r^M \le D_n^M$$

Similarly, the OEM's and IR's optimal decisions can be obtained by solving the KKT necessary conditions, and the optimal results are provided in Proposition 2. Define $c_{r1}^M = \frac{1}{2}q_r(c_n(3-q_r)+q_r-1) - \frac{1}{2}(2-q_r)(1-q_r)r$ and $c_{r2}^M = \frac{q_r(1+c_n-q_r)-2(1-q_r)r}{2-q_r}$.

Proposition 2. The OEM's and IR's optimal results in the main case with licensing are:

(1) In remanufacturing strategy *R1* where the IR collects and remanufactures some of the used products but not all, the existence condition for this strategy is: $c_{r1}^M < c_r < c_{r2}^M$. The optimal pricing decisions for the OEM and the IR are $p_{n-R1}^{M*} = \frac{2+2c_n+c_r-2q_r+3r}{4-q_r}$ and $p_{r-R1}^{M*} = \frac{2c_r+q_r(1+c_r-q_r)+r(q_r+2)}{4-q_r}$, and the corresponding profits are: $\Pi_{OEM-R1}^{M*} = \frac{\left((2+c_r-c_n(2-q_r)-2q_r)^2 q_r + (1-q_r)(q_r(8+(1-c_n)q_r)-8c_r)r - (1-q_r)(8+q_r)r^2\right)}{(4-q_r)^2(1-q_r)q_r}$ and $\Pi_{IR-R1}^{M*} = \frac{\left(q_r(1+c_n-q_r+2r)-2r-c_r(2-q_r)\right)^2}{(4-q_r)^2(1-q_r)q_r}$.

(2) In remanufacturing strategy *R2* where the IR collects and remanufactures all the used products available for remanufacturing, the existence condition for this strategy is: $c_r < c_{r1}^M$. The optimal pricing decisions for the OEM and the IR are $p_{n-R2}^{M*} = \frac{1}{2}\left(1+c_n-(1-c_n)q_r+r(1+q_r)\right)$ and $p_{r-R2}^{M*} = q_r(c_n+r)$, and the corresponding profits are:

$$\prod_{OEM-R2}^{M*}=\frac{1}{4}(1-c_n-r)\big((1-c_n)(1-q_r)+(3+q_r)r\big) \text{ and } \prod_{IR-R2}^{M*}=\frac{1}{2}(1-c_n-r)(q_r(c_n+r)-c_r-r).$$

Similar to Proposition 1, Proposition 2 provides the OEM's and IR's optimal decisions in the main case when the OEM and the IR cooperate with each other through a license agreement. The proposition also provides the conditions for the IR to implement different remanufacturing strategy. The IR will not engage in remanufacturing when the cost of remanufacturing is at a relatively high level (i.e., $c_r > c_{r2}^M$), while it will collect and remanufacture all the used products when the cost of remanufacturing is at a relatively low level (i.e., $c_r < c_{r1}^M$). When the cost of remanufacturing is at a medium level (i.e., $c_{r1}^M < c_r < c_{r2}^M$), the IR will collect and remanufacture some of the used products but not all. Comparing the boundary conditions and the OEM's and IR's optimal pricing decisions in the two remanufacturing strategies in the two cases, Lemma 2 is derived.

Lemma 2. The boundary conditions for the benchmark and main cases are related as follows: $c_{r1}^M < c_{r1}^B$ and $c_{r2}^M < c_{r2}^B$. The OEM's and IR's optimal pricing decisions in strategy *R1* in the benchmark and main cases are related as follows: $p_{n-R1}^{M*} > p_{n-R1}^{B*}$ and $p_{r-R1}^{M*} > p_{r-R1}^{B*}$. The OEM's and IR's optimal pricing decisions in strategy *R2* in the benchmark and main cases are related as follows: $p_{n-R2}^{M*} > p_{n-R2}^{B*}$ and $p_{r-R2}^{M*} > p_{r-R2}^{B*}$.

Lemma 2 provides the comparison of the two cases (with and without licensing) in terms of boundary conditions and optimal pricing decisions. The relationships in Lemma 2 are feasible for any given nonnegative royalty fee (i.e., $r > 0$). From the comparison of the boundary conditions in the two cases, Lemma 2 shows that, in the main case when there is a license agreement between the OEM and the IR, the IR is less likely to collect and remanufacture all the used products (i.e., strategy *R2*) but more likely to choose strategy *R1* as $c_{r1}^M < c_{r1}^B$ is more stringent compared with that in the benchmark case. However, in the main case, the IR is less likely to enter the remanufacturing market whether in terms of strategy *R1* or strategy *R2* as $c_{r2}^M < c_{r2}^B$. This is because, compared with the benchmark case without licensing, paying royalty fee directly increases the IR's marginal cost of remanufacturing, which will directly decrease the profit that the IR can earn from the remanufacturing market and consequently decreases the motivation for the IR to engage in remanufacturing.

The comparison of the boundary conditions in the two cases also implies that, in most scenarios, the IR will choose the same remanufacturing strategy in the two cases (i.e., the benchmark case and the main case) with two exceptions. More specifically, for any $c_r \in (0, c_{r1}^M)$ and $c_r \in (c_{r1}^B, c_{r2}^M)$, the IR will choose the remanufacturing strategies *R2* and *R1* in the two cases, respectively. However, for any $c_r \in (c_{r1}^M, c_{r1}^B)$, the IR will remanufacture all the used products (i.e., strategy *R2*) in the benchmark case but will only remanufacture some of the used products (i.e., strategy *R1*) in the main case. Besides, for any $c_r \in (c_{r2}^M, c_{r2}^B)$, the IR will not engage in remanufacturing when it signs a royalty licensing contract with the OEM but will still remanufacture some of the used products if it chooses to self-develop the remanufacturing technology.

From the comparison of the OEM's and IR's optimal pricing decisions in the two strategies in the two cases, Lemma 2 implies that the royalty licensing contract will induce the two parties (i.e., the OEM and the IR) to increase their sales price for new and remanufactured products. As explained above, the royalty fee in the main case will directly increase the IR's marginal cost of remanufacturing and hence, the IR will increase the sales price of remanufactured products to gain a certain profit margin. Since the OEM also operates in the market strategically, the price increase of remanufactured products indirectly motivates the OEM to increase the sales price for new products. However, it is worth to note that the price raise of new products is greater than that of remanufactured products as $p_{n-R1}^{M*} - p_{r-R1}^{M*} > p_{n-R1}^{B*} - p_{r-R1}^{B*}$ and $p_{n-R2}^{M*} - p_{r-R2}^{M*} > p_{n-R2}^{B*} - p_{r-R2}^{B*}$. As such, compared with new products in the main case with licensing, remanufactured products will become more competitive with a relatively lower price. This means that the licensing cooperation between the OEM and the IR will intensify the competition between new and remanufactured products. This result is completely different from Jiang and Shi [25]. They examined a licensing cooperation of a general product between an entrant and an incumbent in the technology innovation context. They found that a royalty contract between two competitive firms would induce the two firms to increase their sales prices and soft price competition, and thus, has a competition-alleviating effect on competitive firms. This study extended their research from a general product case to the remanufacturing market where there exists both competition and cooperation between the OEM and the IR. We show that price competition is indeed alleviated as price difference between new and remanufactured products will increase. However, competition-alleviating effect will not exist in the new and remanufactured products competition context as remanufactured products would be sold at a more competitive price.

Several reasons account for why the competition between new and remanufactured products will intensify when there is a licensing contract between the OEM and the IR. First, the existence of remanufactured products will cannibalize customers' demand for new products, and the cannibalization effect will become more intense if the price increase of new products is greater than that of remanufactured products. Hence, in the main case with licensing, the OEM's profit from new products will be cannibalized more compared with that in the benchmark case without licensing. Second, the OEM's profit loss from new products can be offset by the royalty fee charged to the IR. The price difference between new and remanufactured products will increase in the main case, which increases the competitiveness of remanufactured products and consequently increases the IR's profit from remanufacturing. The increase in the sales quantity of remanufactured products correspondingly increases the OEM's royalty fee and therefore the OEM's profit. The profit gain outweighs the lost, motivating the OEM to charge a higher sales price for new products. In addition, in contrast with the previous literature (e.g. Jiang and Shi [25]), our model incorporates the special tie between new and remanufactured products. Thus, the number of used products that can be remanufactured is strictly limited by the number of cores that can be collected. In general practice, the quality of remanufactured products is smaller than that of new products. As such, the OEM has a good anticipation of the competition coming from the IR and hence, it can charge a higher sales price for new products even though it will push some customers to purchase the competitor's (i.e., the IR) products.

5.2. IR's Quality Decision

To investigate the IR's optimal quality choice for remanufactured products, it is necessary to determine which production strategy (i.e., high quality with high production cost and low-quality with low production cost) can yield a higher profit for the IR. Therefore, the IR's optimal profit functions in the two production strategies are obtained by substituting $q_r = q_r^H$, $c_r = c_r^H$, $q_r = q_r^L$ and $c_r = c_r^L$ into Proposition 2. Comparing the IR's profit in the two production and remanufacturing strategies, the IR's optimal choice quality for remanufactured products is summarized in Lemma 3.

Lemma 3. In the main case with licensing, the IR's optimal quality choice for remanufactured products in the two remanufacturing strategies is:

(1) In remanufacturing strategy *R1*, for any $c_r^H, c_r^L \in (c_{r1}^M, c_{r2}^M)$ the IR will choose the high-quality production strategy if $c_r^L < c_r^H < c_{r3}$ and the low-quality production strategy otherwise, where

$$c_{r3} = \frac{q_r^H\left(c_n + (1-q_r^H)\right) - R\left((1+c_n-q_r^L)q_r^L - c_r^L(2-q_r^L)\right) - 2r(1-q_r^H - R(1-q_r^L))}{(2-q_r^H)}. \text{ Moreover, } \frac{dc_{r3}}{dr} > 0 .$$

(2) In remanufacturing strategy *R2*, for any $c_r^H, c_r^L \in (0, c_{r1}^M)$, the IR will choose the high-quality production strategy if $c_r^L < c_r^H < c_{r4}$ and the low-quality production strategy otherwise, where

$$c_{r4} = c_r^L + c_n(q_r^H - q_r^L) + r(q_r^H - q_r^L). \text{ Moreover, } \frac{dc_{r4}}{dr} > 0 .$$

Consistent with Lemma 1, Lemma 3 also derives the IR's optimal quality choice for remanufactured products in the two remanufacturing strategies when the IR engages in remanufacturing by obtaining the remanufacturing technology from the OEM. The IR will choose the high-quality production strategy when the production cost of that strategy is lower than a threshold. Otherwise, the IR should choose the low-quality production strategy. In addition, the lemma shows that the thresholds c_{r3} and c_{r4} increase with the royalty fee r, which implies that the parameter region of c_r^H will increase as the royalty fee increases. As such, the region where the IR chooses the high-quality production strategy will increase with the royalty fee. Intuitively, the IR's profit decreases with the increase of the royalty fee in both high-quality and low-quality production strategy. However, the results show that the IR is more likely to adopt the high-quality production strategy when the OEM increases the royalty fee. The reasons are provided in the following context.

Recall that in the benchmark case without licensing, the IR will choose the high-quality production option in remanufacturing strategy *R1* if $c_r^H < c_{r1}$ and the low-quality production option otherwise. In remanufacturing strategy *R2*, the IR will choose the high-quality production option if $c_r^H < c_{r2}$. Comparisons of threshold c_{r1} with c_{r3}, and c_{r2} with c_{r4} enable us to examine the impact of the royalty contract on IR's optimal quality choice of remanufactured products.

Lemma 4. For any given nonnegative royalty fee (i.e., $r > 0$), there exist $c_{r3} > c_{r1}$ and $c_{r4} > c_{r2}$.

Lemma 4 compares the threshold conditions in the two cases without and with licensing contract between the OEM and the IR. Based on Lemma 4, the IR's optimal quality choice for remanufactured products in the two cases is characterized in Figure 2, where H and L in the figure stand for the high-quality and low-quality production strategy, respectively. Lemma 4 and Figure 2 show that, compared with the benchmark case without licensing, the IR is more likely to adopt the high-quality production strategy in the main case regardless of the remanufacturing strategy decision (i.e., *R1* and *R2*). The royalty contract motivates the IR to choose the high-quality production strategy over the low-quality production strategy by increasing the parameter region. The quality difference between new and remanufactured products will decrease if the IR adopts the high-quality production strategy, indicating that the royalty contract between the OEM and the IR has a competition-intensifying effect from the product quality perspective. This result is also completely different with Jiang and Shi [25]. They showed that the intercompetitor licensing between an entrant and an incumbent will induce the entrant to choose two different production strategies which are differentiated by the innovation of the core technology. They also found that the quality competition can either be intensified or alleviated after the cooperation. However, this study shows that the IR will always choose to produce high-quality remanufactured products when there is an intercompetitor licensing contract between the OEM and the IR, which leads to a competition-intensifying effect on product quality.

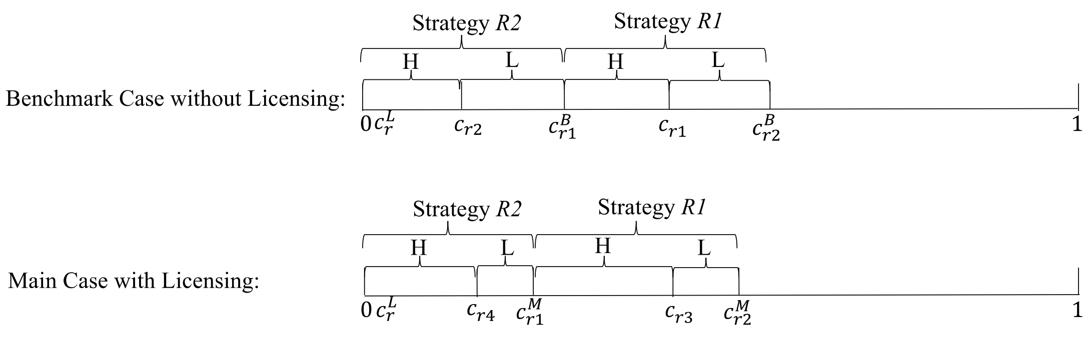

Figure 2. The IR's optimal quality choice for the remanufactured products in the two cases.

Recall that Lemma 2 shows that the licensing contract will alleviate price competition between new and remanufactured products by inducing the OEM and the IR to increase their sales price, and the

OEM will always increase the sales price of new products to a larger degree. However, Lemma 4 shows that the royalty licensing contract will intensify quality competition between new and remanufactured products. The overall impact of the licensing contract on the IR is to increase the competitiveness of remanufactured products. On the one hand, compared with new products, remanufactured products always have a price advantage in the main case as the IR will always increase the sales price of the remanufactured product to a smaller degree than that of new products. On the other hand, the royalty licensing contract motivates the IR to adopt the high-quality production strategy, which will decrease the quality difference between new and remanufactured products. However, these two positive impacts do not necessarily mean that the royalty licensing contract dominates the self-developing technology strategy. In other words, how the IR interferes with the remanufacturing market depends on certain market conditions. For instance, the IR's attitude depends on how significantly the royalty contract can improve the competitiveness of the remanufactured products in terms of either price or quality. In the following, we will discuss the threshold conditions for the IR to accept the royalty licensing contract offered by the OEM.

The IR will choose to obtain the remanufacturing technology licensed from the OEM rather than self-developing the technology if and only if the licensing contract can give the IR a higher profit by anticipating the quality choice of remanufactured products. Therefore, to obtain the threshold condition for the IR to accept the contract, it is sufficient to compare the IR's profit in the two cases (i.e., benchmark case and main case). The comparison results are summarized in Proposition 3.

Proposition 3. The IR prefers obtaining the remanufacturing technology from the OEM to self-developing the technology if and only if $r \le \bar{r}$, where $\bar{r}$ is the threshold condition defined by the following conditions (the detailed expressions for the threshold are provided in the Appendix):

(1) If the IR adopts remanufacturing strategy *R1* in both benchmark and main cases, thus, for any $c_r^H, c_r^L \in (c_{r1}^B, c_{r2}^M)$, we have $\bar{r} = \bar{r}_1^{HH}$ if $c_{r1}^B \le c_r^L < c_r^H < c_{r1}$, $\bar{r} = \bar{r}_1^{LH}$ if $c_{r1} < c_r^H < c_{r3}$, and $\bar{r} = \bar{r}_1^{LL}$ if $c_{r3} < c_r^H < c_{r2}^M$.

(2) If the IR adopts remanufacturing strategy *R2* in the benchmark case but adopts remanufacturing strategy *R1* in the main case, thus, for any $c_r^H, c_r^L \in (c_{r1}^M, c_{r1}^B)$, we have $\bar{r} = \bar{r}_2^{LH}$.

(3) If the IR adopts remanufacturing strategy *R2* in both benchmark and main cases, thus, for any $c_r^H, c_r^L \in (0, c_{r1}^M)$, we have $\bar{r} = \bar{r}_2^{HH}$ if $0 \le c_r^L < c_r^H < c_{r2}$, $\bar{r} = \bar{r}_3^{LH}$ if $c_{r2} < c_r^H < c_{r4}$, and $\bar{r} = \bar{r}_2^{LL}$ if $c_{r4} < c_r^H < c_{r1}^M$.

For the OEM, the main case will be degraded to the benchmark case if the royalty fee is zero as it has no effect on the OEM's optimal pricing decisions and the OEM will earn the same level of profit as in the benchmark case. For the IR, it will reject the royalty licensing contract and choose to self-develop the remanufacturing technology if the royalty fee is higher than the threshold defined the Proposition 3. Hence, the condition for reaching a royalty licensing contract between the OEM and the IR is $0 < r \le \bar{r}$.

As such, any royalty fee in the interval is mutually acceptable for the OEM and the IR. To examine the impact of the royalty fee on the IR's optimal quality choice for remanufactured products, lemma 5 is provided.

Lemma 5. The impact of the royalty licensing contract on the IR's optimal quality choice for remanufactured products is characterized as follows:

(1) If the IR adopts remanufacturing strategy *R1* in both benchmark and main cases, for any $c_r^H, c_r^L \in (c_{r1}^B, c_{r2}^M)$, the royalty licensing contract will induce the IR to choose the high-quality production strategy if $c_{r1} < c_r^H < c_{r3}$, and have no impact on the IR's optimal quality choice otherwise.

(2) If the IR adopts remanufacturing strategy *R2* in the benchmark case but adopts remanufacturing strategy *R1* in the main case, for any $c_r^H, c_r^L \in (c_{r1}^M, c_{r1}^B)$, the royalty licensing contract will always induce the IR to choose the high-quality production strategy.

(3) If the IR adopts remanufacturing strategy *R2* in both benchmark and main cases, for any $c_r^H, c_r^L \in (0, c_{r1}^M)$, the royalty licensing contract will induce the IR to choose the high-quality production strategy if $c_{r2} < c_r^H < c_{r4}$, and have no impact on the IR's optimal quality choice otherwise.

Lemma 5 shows how the royalty fee affects the IR's product quality option in the two remanufacturing strategies. It implies that the royalty licensing contract does not always affect the IR's optimal quality choice for remanufactured products. When the product quality decision depends on the royalty licensing contract, the contract will always induce the IR to choose the high-quality production strategy. When the IR adopts the same remanufacturing strategy in both benchmark and main cases, the royalty licensing contract will not affect the IR's optimal quality choice in most scenarios but with an exception. However, when the IR adopts different remanufacturing strategies in the two cases, the license cooperation will always affect the IR's quality choice of remanufactured products and motivate the IR to remanufacture with a higher quality.

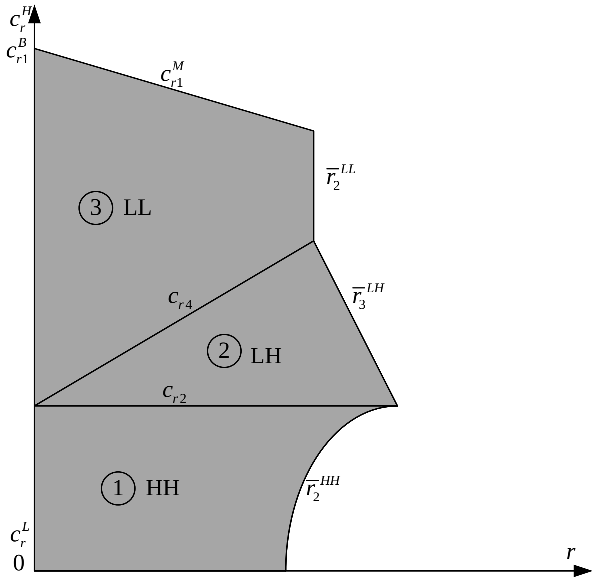

Figure 3. The IR's optimal quality choice and threshold condition.

Figure 3 illustrates the impact of royalty licensing contract on the IR's optimal quality choice for remanufactured products when the IR adopts *R2* remanufacturing strategy in both benchmark and main cases. In the figure, the shaded regions show the scenarios where the royalty licensing contract is mutually acceptable for both the OEM and the IR, whereas the unshaded regions show the scenario where the royalty fee is so high that the royalty licensing contract is unacceptable for the IR. The letters in each region specify the IR's optimal production strategy for the remanufactured products in the benchmark case and main case, respectively. For instance, HH (LL) stands for the scenario where the IR chooses to produce remanufactured products at the high-quality (low-quality) level in the benchmark and main cases. LH stands for the scenario where the IR chooses to produce remanufactured products at a low-quality level in the benchmark case but decides to remanufacture at a high-quality level in the main case. The impact of the licensing contract on the IR's optimal quality choice for remanufactured products when the IR adopts *R1* or when the IR adopts different remanufacturing strategy in the two cases has the same characteristics as that of Figure 3. Hence, those two scenarios are omitted in this discussion.

In region 1 (i.e., HH region), the IR will choose the high-quality level regardless of whether it has a royalty contract with the OEM. This is because, in this region, the IR can produce remanufactured products at a high-quality level with a relatively low cost (i.e., $0 \le c_r^L < c_r^H < c_{r2}$). As such, remanufacturing used products at a high-quality is cost-efficient and hence, the IR should always choose the high-quality production strategy regardless of the royalty contract cooperation decision. Similarly, in region 3 (i.e., LL region), the IR will choose the low-quality level regardless of the royalty contract cooperation decision as the production cost for the high-quality products is at a relatively high level (i.e., $c_{r4} < c_r^H < c_{r1}^M$). However, licensing cooperation with the OEM on the remanufacturing technology will motivate the IR to remanufacture used products at the high-quality level if the corresponding production cost is at a medium level (i.e., $c_{r2} < c_r^H < c_{r4}$). On the one hand, if the IR chooses to self-develop the remanufacturing technology, it will choose the low-quality production strategy as remanufacturing used products with a high-quality level is cost inefficient. On the other hand, as implied in Lemmas 2 and 4, the royalty licensing contract can induce both firms to increase their sales price for new and remanufactured products and the OEM will always increase its sales price a larger degree than the IR, which will give the IR a price advantage in the market. The competitive position of the remanufactured products can be further enhanced if the IR chooses the high-quality production strategy as customers can purchase a high-quality product with a lower price. Therefore, in this parameter region, the IR should remanufacture used products at the high-quality level when there is a licensing contract, and when the royalty fee is acceptable.

So far, it has been proven that, compared with the benchmark case without licensing, a royalty licensing contract is mutually acceptable for both the OEM and the IR in a wide range of parameter values and royalty fees (see Proposition 3 and Figure 3). In practice, the specific value of the royalty fee on a licensing cooperation contract depends on the relative bargaining power of the OEM and the IR. Therefore, the optimal royalty fee may fall anywhere within the mutually acceptable region. In this paper, we assume that the OEM is the leader in the licensing cooperation and determines the royalty fee. The OEM's royalty fee decision is examined in the following subsection. Before moving to examine the OEM's royalty fee decision, it is necessary to investigate the OEM's and IR's licensing cooperation decision with an exogenously given royalty fee.

Intuitively, the OEM will choose not to license its remanufacturing technology to the IR if the total royalty fee paid by the IR is much lower than the incurred R&D cost to self-developing the technology. This is because the low royalty fee can give the IR a competitive advantage in the market by significantly saving its production cost. Similarly, it is intuitive to infer that the IR will not try to seek licensing cooperation from the OEM if the royalty fee charged by the OEM is too high. As such, self-developing the technology is much more cost-efficient. However, the existence of the wide range of parameter values and royalty fees described in Proposition 3 and Figure 3 shows that such intuitions may not always hold and thus, cannot lead to sound decisions for the OEM and the IR.

Proposition 4. When the royalty fee is exogenously given (i.e., without knowing the OEM's optimal royalty fee decision), the OEM will benefit from a royalty licensing contract even when the royalty fee is at a low level, and the IR will benefit from the royalty licensing contract even when the royalty fee is at a relatively high level.

There are several wide parameter regions that make the royalty licensing contract beneficial to both the OEM and the IR. For the OEM, it benefits from the licensing contract for two main reasons: the royalty fee and increase of the sales price. The OEM's optimal pricing decision will not be affected by the royalty fee and will earn the same level of profits as in the benchmark case without licensing if the royalty fee is zero. Hence, any nonnegative royalty fee can motivate the OEM to share partial profit from remanufacturing and make strategically decisions in response to the IR's interference with the remanufacturing market. In addition, the OEM will always raise the sales price for new products when there is a licensing contract. The increase of the sales price can increase the OEM's profit margin though the OEM may lose some new product sales. However, the positive impact of raising sales price outweighs the negative impact of the demand losing. Furthermore, the number of products that can be remanufactured is always smaller than the number of cores that can be collected. This indicates that the OEM can always limit the entrance of the IR by limiting the IR's remanufacturing quantity.

It is obvious that the IR can benefit from the licensing contract if the IR only needs to pay a low royalty fee, especially when the royalty fee is much lower than the incurred R&D cost for self-developing the remanufacturing technology. However, a licensing contract is still acceptable even if the IR has to pay a relatively high royalty fee. On the one hand, the IR will also increase the sales price of remanufactured products when there is licensing contract. However, it will always raise the sales price by a smaller degree than the OEM, which will create a price advantage for the IR. On the other hand, the licensing cooperation will always induce the IR to produce remanufactured products at the high-quality level, which will further increase the competitiveness of remanufactured products. Therefore, the IR will benefit from the technology licensing even when the royalty fee is at a relatively high level.

5.3. OEM's Royalty Fee Decision

In anticipating the IR's optimal quality and pricing decisions, the OEM determines the optimal unit royalty fee with the goal of maximizing its own profit when there is a license cooperation between the OEM and the IR. As shown in Proposition 2, the OEM's profit function when the IR adopts *R1* remanufacturing strategy is $\prod_{OEM-R1}^{M*}=\frac{(2+c_r-c_n(2-q_r)-2q_r)^2q_r+(1-q_r)(q_r(8+(1-c_n)q_r)-8c_r)r-(1-q_r)(8+q_r)r^2}{(4-q_r)^2(1-q_r)q_r}$, where $(q_r,c_r)=(q_r^H,c_r^H)$ if $c_r^H<c_{r3}$ and $(q_r,c_r)=(q_r^L,c_r^L)$ otherwise. In remanufacturing strategy *R2*, the OEM's profit function is $\prod_{OEM-R2}^{M*}=\frac{1}{4}(1-c_n-r)((1-c_n)(1-q_r)+(3+q_r)r)$, where $(q_r,c_r)=(q_r^H,c_r^H)$ if $c_r^H<c_{r4}$ and $(q_r,c_r)=(q_r^L,c_r^L)$ otherwise. In the two remanufacturing strategies, the OEM maximizes $\prod_{OEM-R1}^{M*}$ and $\prod_{OEM-R2}^{M*}$ respectively over r within the constraint $0<r\le\bar{r}$. We can prove that the OEM's profit functions are concave in the unit royalty fee, which leads to an inverted-U-shape curve with respect to the royalty fee. As such, the OEM is not necessarily better off when charging a high royalty fee. The OEM's optimal royalty fee is summarized in Proposition 5.

Proposition 5. The OEM's optimal royalty fee is $r=r^*$, where r^* is given by the following conditions:

(1) For any $c_r^H, c_r^L \in (c_{r1}^B, c_{r2}^M)$, when the IR adopts remanufacturing strategy *R1* in both the benchmark and main cases,

(a) $r^* = \min\left\{\overline{r_1}^{HH}, r_1^H\right\}$ if $c_{r1}^B \le c_r^L < c_r^H < c_{r1}$,

(b) $r^* = r_1^{LH*} = \max\left\{\frac{(c_r^H - c_{r1})(2-q_r^H)}{2(R(1-q_r^L)-(1-q_r^H))}, \min\left\{\overline{r_1}^{LH}, r_1^H\right\}\right\}$ if $c_{r1} < c_r^H < \overline{c_{r3}}$ and $\Pi_{OEM-R1}^{M-H*}(r_1^{LH*}) \ge \Pi_{OEM-R1}^{M-L*}(r_1^{LL*})$,

(c) $r^* = r_1^{LL*} = \min\left\{\frac{(c_r^H - c_{r1})(2-q_r^H)}{2(R(1-q_r^L)-(1-q_r^H))}, r_1^L\right\}$ if $c_{r1} < c_r^H < \overline{c_{r3}}$ and $\Pi_{OEM-R1}^{M-H*}(r_1^{LH*}) < \Pi_{OEM-R1}^{M-L*}(r_1^{LL*})$,

(d) $r^* = \max\left\{\frac{(c_{r2}^B - c_r^H)(2-q_r^L)}{2(1-q_r^L)}, \min\left\{\overline{r_1}^{LL}, r_1^L\right\}\right\}$ if $\overline{c_{r3}} < c_r^H < \overline{c_{r2}^M}$,

where $r_1^H = \frac{-8c_r^H + q_r^H(8+q_r^H - c_n q_r^H)}{2(8+q_r^H)}$, $r_1^L = \frac{-8c_r^L + q_r^L(8+q_r^L - c_n q_r^L)}{2(8+q_r^L)}$, $\overline{c_{r3}} = c_{r3}\big|_{r=\overline{r_1}^{LL}}$, and $\overline{c_{r2}^M} = c_{r2}^M\big|_{q_r=q_r^L, r=\overline{r_1}^{LL}}$.

(2) For any $c_r^H, c_r^L \in (c_{r1}^M, c_{r1}^B)$, when the IR adopts remanufacturing strategy *R2* in the benchmark case but adopts remanufacturing strategy *R1* in the main case,

(a) $r^* = r_2^{LH*} = \max\left\{\frac{2(c_{r1}^B - c_r^H)}{(2-q_r^L)(1-q_r^L)}, \min\left\{\overline{r_2}^{LH}, r_1^H\right\}\right\}$ if $\overline{c_{r1}^M} < c_r^H < \overline{c_{r2}^B}$ and $\Pi_{OEM-R1}^{M-H*}(r_2^{LH*}) \ge \Pi_{OEM-R2}^{B-L*}(r_2^{LL*})$,

(b) $r^* = r_2^{LL*} = \min\left\{\frac{2(c_{r1}^B - c_r^H)}{(2-q_r^L)(1-q_r^L)}, r_1^L\right\}$ if $\overline{c_{r1}^M} < c_r^H < \overline{c_{r2}^B}$ and $\Pi_{OEM-R1}^{M-H*}(r_2^{LH*}) < \Pi_{OEM-R2}^{B-L*}(r_2^{LL*})$,

where $\overline{c_{r1}^M} = c_{r1}^M\big|_{q_r=q_r^L, r=\overline{r_2}^{LL}}$.

(3) For any $c_r^H, c_r^L \in (0, c_{r1}^M)$, when the IR adopts remanufacturing strategy *R2* in both the benchmark and main cases,

(a) $r^* = \min\left\{\overline{r_2}^{HH}, r_2^H\right\}$ if $0 \le c_r^L < c_r^H < c_{r2}$, $r^* = r_3^{LH*} = \max\left\{\frac{c_r^H - c_{r2}}{q_r^H - q_r^L}, \min\left\{\overline{r_3}^{LH}, r_2^H\right\}\right\}$ if $c_{r2} < c_r^H < \overline{c_{r4}}$ and $\Pi_{OEM-R2}^{M-H*}(r_3^{LH*}) \ge \Pi_{OEM-R2}^{M-L*}(r_3^{LL*})$,

(b) $r^* = r_3^{LL*} = \min\left\{\frac{c_r^H - c_{r2}}{q_r^H - q_r^L}, r_2^L\right\}$ if $c_{r2} < c_r^H < \overline{c_{r4}}$ and $\Pi_{OEM-R2}^{M-H*}(r_3^{LH*}) < \Pi_{OEM-R2}^{M-L*}(r_3^{LL*})$,

(c) $r^* = \max\left\{\frac{2(c_{r1}^B - c_r^H)}{(2-q_r^L)(1-q_r^L)}, \min\left\{\overline{r}_2^{LL}, r_2^L\right\}\right\}$ if $\overline{c_{r4}} < c_r^H < \underline{c_{r1}^M}$,

where $r_2^H = \frac{(1-c_n)(1+q_r^H)}{3+q_r^H}$, $r_2^L = \frac{(1-c_n)(1+q_r^L)}{3+q_r^L}$, $\overline{c_{r4}} = c_{r4}\big|_{r=\overline{r}_2^{LL}}$ and $\underline{c_{r1}^M} = c_{r1}^M\big|_{q_r=q_r^L, r=\overline{r}_2^{LL}}$.

Proposition 5 shows the OEM's optimal royalty fee decision in anticipating the IR's different remanufacturing strategies. The OEM sets the royalty fee that maximizes its own profit considering the IR's participating condition. The OEM's optimal royalty fee decision when the IR adopts the *R2* remanufacturing strategy is depicted in Figure 4. The OEM's optimal royalty fee decision in the other two scenarios exhibits similar characteristics as in the scenario when the IR adopts the *R2* remanufacturing strategy. Hence, those two scenarios are not illustrated in the figures for brevity. Proposition 5 and Figure 4 imply that a royalty licensing contract is still achievable and mutually beneficial to the OEM and the IR even when the OEM endogenously determines the royalty fee.

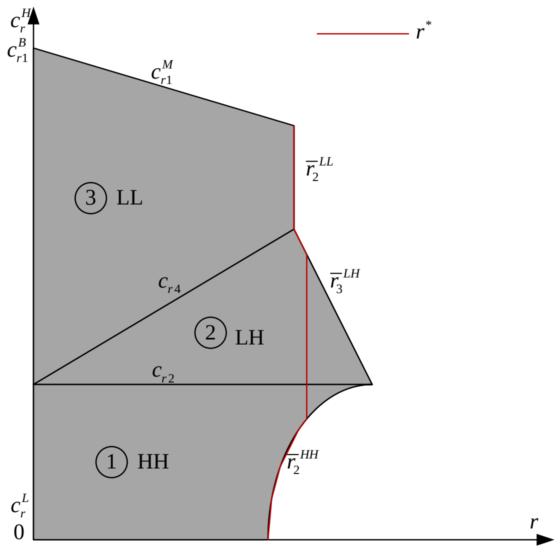

Figure 4. The OEM's optimal royalty fee.

Observation 1. When the royalty fee is endogenously determined by the OEM, it may benefit from a royalty licensing contract even when the total royalty fee paid by the IR is smaller than the incurred R&D cost for the IR self-developing the remanufacturing technology, and the IR will benefit from the technology licensing even when the total paid royalty fee is larger than the incurred R&D cost for the IR self-developing the remanufacturing technology.

Recall that, Proposition 4 shows that a loyalty licensing contract is mutually beneficial for the OEM and the IR even when the exogenous royalty fee is relatively low for the OEM or the exogenous royalty fee is relatively high for the IR. Observation 1 further shows that this result still holds even when the OEM strategically determines the royalty fee. Intuitively, the IR will choose to self-develop the remanufacturing technology if the incurred R&D cost for developing that technology is lower than the total royalty fee paid to the OEM. However, Observation 1 shows that the IR prefers licensing to self-developing even if it has to pay a high royalty fee. Observation 1 is illustrated by numerical examples in which the total royalty fee paid is larger than the fixed R&D cost. Note that the value settings for the following numerical examples are randomly chosen within the valid parameters range for illustration purpose, and other sets of valid parameters are also applicable to numerically illustrate the results of Observation 1. The above analysis shows that the marginal production cost for remanufactured products and the fixed R&D cost incurred for self-developing technology play a vital role in affecting the OEM's and the IR's licensing cooperation decision. Therefore, customers' valuation for high- and low-quality levels of remanufactured products are respectively fixed to 0.8 and 0.5, and the marginal production cost of new products is fixed to 0.3. In the first scenario, assuming that the marginal production cost for high- and low-quality levels of remanufactured products are both at relatively low levels, i.e., $(q_r^H, c_r^H) = (0.8, 0.15)$, $(q_r^L, c_r^L) = (0.5, 0)$, $c_n = 0.3$, and $F = 0.03$, in equilibrium, $r^* = 0.1394$, $r^* D_{r-R2}^{M*} = 0.0391 > F = 0.03$, and $\Pi_{IR-R2}^{M-L*} = 0.025 \geq \Pi_{IR-R2}^{B-L*} = 0.025$. In the second scenario, assuming that the marginal production cost for high- and low-quality levels of remanufactured products are both at relatively high levels, i.e., $(q_r^H, c_r^H) = (0.8, 0.27)$, $(q_r^L, c_r^L) = (0.5, 0.15)$, $c_n = 0.3$, and $F = 0.003$, in equilibrium $r^* = 0.029$, $r^* D_{r-R2}^{M*} = 0.0048 > F = 0.003$, and $\Pi_{IR-R1}^{M-L*} = 0.007 \geq \Pi_{IR-R1}^{B-L*} = 0.007$. The two numerical examples show that a royalty licensing contract is mutually acceptable and can give the OEM and the IR a higher profit even if the total royalty fee paid by the IR is larger than the incurred R&D cost. It is also possible to illustrate that a royalty licensing contract is achievable between the OEM and the IR when the total royalty fee paid by the IR is smaller than the incurred R&D cost. Due to the length of the paper, the corresponding numerical examples are omitted.

6. Extensions

In this section, the robustness of the results will be verified by considering several alternative model settings and assumptions. First, compared with self-develop remanufacturing technology in-house, one assumption is made that the royalty licensing contract can increase customers' willingness to pay for remanufactured products. Second, instead of assuming that the IR can choose between two quality levels for remanufactured products, it is assumed that the quality of remanufactured products is a continuous decision variable. Finally, another game sequence is considered, which allows the OEM to determine the royalty fee after observing the IR's quality decision for remanufactured products.

6.1. Customers' willingness to pay for the quality will increase after licensing

In the main model, the assumption is that customers' willingness to pay for remanufactured products is identical in the benchmark and the main cases. This assumption is reasonable because whether the remanufactured products produced by the technology self-developed by the IR or licensed from the

OEM present the same quality. In this extension, this assumption is replaced by assuming that customers have a higher willingness to pay for remanufactured products if the IR obtains remanufacturing technology license from the OEM even though the products produced by the IR's self-developed technology have the same quality. Subramanian and Subramanyam [50] find that products remanufactured by OEMs or their authorized parties are purchased at higher prices than those remanufactured by IRs. This indicates that customers' willingness to pay for the products remanufactured by OEMs or their authorized parties are higher than that of the products remanufactured by unauthorized IRs. Liu, et al. [12] and Zhou, et al. [13] also have similar assumptions based on practical industry examples.

The OEM's and IR's optimal decisions are the same as in the benchmark case without licensing in Section 4 as the OEM and the IR operate independently in the market. Therefore, in remanufacturing strategy *R1*, the IR will choose the high-quality production strategy if $c_r^L < c_r^H < c_{r1}$ and the low-quality production strategy otherwise. In remanufacturing strategy *R2*, the IR will choose the high-quality production strategy if $c_r^L < c_r^H < c_{r2}$ and the low-quality production strategy otherwise. In the main case with licensing, customers' willingness to pay for remanufactured products will increase with the royalty licensing cooperation. Let $\alpha > 1$ denote the increase of customers' willingness to pay for remanufactured products. Hence, customers gain a utility of $u_r = \theta\alpha q_r - p_r$ if they purchase a remanufactured product, while the utility customers gained if they purchase a new product remains the same. Customers' demand for new and remanufactured products are then: $D_n = 1 - \frac{p_n - p_r}{q_n - \alpha q_r}$ and $D_r = \frac{p_n - p_r}{q_n - \alpha q_r} - \frac{p_r}{\alpha q_r}$. Given that the increase of customers' willingness to pay for remanufactured products only affects the structures of customers' demand for new and remanfuactured products, the sequence of the game does not change and the OEM's and IR's optimal decisions can be obtained using the same approach as in Section 4. Then, the OEM's and IR's optimal decisions are derived by using backward induction, and the equilibrium outcomes are provided in the Appendix.

The findings are compared with the key results in Section 5. Specifically, with the increase of customers' willingness to pay for remanufactured products, the OEM and the IR will still respectively increase their sales prices for new and remanufactured products after the licensing cooperation. Moreover, a royalty licensing contract will still induce the IR to remanufacture the used product at a high-quality level. However, the conclusion that the OEM will always increase its sales price than the IR may not hold when customers' willingness to pay for remanufactured products increases with licensing. This is because the cannibalization effect between new and remanufactured products will further increase if the licensing leads to a higher willingness to pay, and it will further decrease the OEM's profit. Thus, the OEM should not further increase the sales price of new products. In addition, the sales price of new products decreases with α , and the sales price of remanufactured products increases with α . Consequently, the price competition between new and remanufactured products may be intensified if α is sufficiently high. As such, the OEM can earn more profit by selling more new products to the market.

6.2. The IR's Quality Choice is Endogenous and Continuous

To derive closed-form solutions, it is assumed in Sections 4 and 5 that the IR can only choose between two quality levels for remanufactured products (high-quality and low-quality production strategies). This assumption is reasonable as the dual-level quality strategy is consistent with real-world applications. In this extension, the dual-level quality assumption is relaxed by assuming that the IR's quality decision for remanufactured products is a continuous variable. Chen and Chen [3] differentiated remanufactured products from refurbished products and argued that the refurbishers can decide the quality of the refurbished product as a continuous variable at their best as the quality of refurbished products is unregulated. Consistent with Chen and Chen [3], this extension allows the IR to determine its quality level in a continuous region. However, the product is still named as remanufactured products. The impact of royalty licensing contract on the IR's optimal quality decisions will be examined. The sequence of the game remains the same as in Sections 4 and 5. The quality level of new products is q_n , the quality level of remanfuactured products is q_r , and the associated marginal costs of reaching new and remanufactured products to a certain quality level are $k_n q_n{}^2$ and $k_r q_r{}^2$, respectively. This form of cost function is widely used in operational research literature, such as Atasu and Souza [51], Örsdemir, et al. [43], and Chen and Chen [3]. Assume $k_r = \beta k_n$, where $\beta \in (0,1)$ is an indicator of the cost advantage of remanufactured products [51]. Consistent with Debo, et al. [52], Ferrer and Swaminathan [53] and Örsdemir, et al. [43], the cost of all manufacturing- and remanufacturing-related activities is included in the marginal cost. In addition, the quality level of new products is normalized to 1 as the baseline to examine the impact of licensing contract on the IR's optimal quality choice.

The complexity of the multistage game makes the solutions intractable. Hence, numerical studies are employed to verify the robustness of the findings in Sections 4 and 5. Assume that $k_n = 0.5$, $\beta = 0.8$, and $F = 0.03$. This set of parameters indicates that the production cost for new products with a quality level q_n is $0.5 q_n{}^2$, the production cost for remanufactured products with a quality level is $0.4 q_r{}^2$, and the fixed cost incurred for self-developing technology is 0.03. In the benchmark case without licensing, the IR adopts remanufacturing strategy *R2*, $q_r^* = 0.625$, $\Pi_{OEM-R2}^{B*} = 0.0234$ and $\Pi_{IR-R2}^{B*} = 0.0091$. In the main case with licensing, the IR also adopts remanufacturing strategy *R2*, $q_r^* = 0.9167$, $r^* = 0.2333$, $\Pi_{OEM-R2}^{M*} = 0.0637$ and $\Pi_{IR-R2}^{M*} = 0.0137$. It can be concluded that the royalty licensing contract also motivates the IR to remanufacture the used products at a high-quality level. Therefore, the results obtained in the main models are still valid when the IR's quality level decision can take values from a continuous region. Although these results are not analytically proven in all parameter regions, we do find that the main results hold in the numerical example analyzed.

6.3. Royalty Fee Decision after the IR's Quality Decision

In the main model, it is assumed that the OEM is the leader in the royalty licensing cooperation and therefore, the OEM determines the unit royalty fee before the IR decides the quality level of remanufactured products. This assumption is reasonable for two reasons. On the one hand, the IR's decision on purchasing the remanufacturing technology or self-developing the technology is less flexible than that of product quality. On the other hand, the OEM always leads the royalty cooperation and decides the royalty fee first before any cooperation agreement is reached as the new product is still its core business in the market. In this extension, the game sequence is described as follows. The IR makes the quality decision for remanufactured products first, and the OEM decides the royalty fee after observing the IR's quality decision. Other settings of this extension model are the identical to those in the benchmark and main cases.

Since there is no licensing cooperation, the optimal decisions in the benchmark case without licensing remain the same. Hence, for any $c_r^H, c_r^L \in (c_{r1}^B, c_{r2}^B)$ when the IR chooses the *R1* remanufacturing strategy, $q_r = q_r^H$ if $c_r^L < c_r^H < c_{r1}$ and $q_r = q_r^L$ otherwise; for any $c_r^H, c_r^L \in (0, c_{r1}^B)$ when the IR chooses the *R2* remanufacturing strategy, $q_r = q_r^H$ if $c_r^L < c_r^H < c_{r2}$ and $q_r = q_r^L$ otherwise. While in the main case with licensing, the IR will make the quality decisions of remanufactured products in anticipating the OEM's royalty fee decision. In this extension, the OEM will set a royalty fee mutually acceptable for the two parties after observing the IR's quality decision. The OEM's and IR's optimal decisions can be obtained using the same approach as in the main analysis, and the equilibrium outcomes are presented in the Appendix.

In the main analysis, the results show that the licensing of the remanufacturing technology can always induce the IR to produce remanufactured products at a high-quality level. In this extension, with the change of the game sequence, the IR may choose to produce remanufactured products at a low-quality level after gaining the remanufacturing technology from the OEM. This is because, with the change of the game sequence, the IR determines the optimal quality level before the OEM's decision on the royalty fee. The remanufactured products have already gained a price advantage after the licensing cooperation. Thus, the IR can strategically choose to produce remanufactured products at a low-quality level by incurring a lower cost. In summary, the results from the main analysis on the impact of the licensing on the OEM's and IR's optimal decisions, and on the IR's optimal quality decisions remain qualitatively the same even if the OEM determines the royalty fee after observing the IR's quality decision.

7. Conclusions and managerial implications

7.1. Concluding remarks

This study examines the economic and strategic implications of intercompetitor licensing of remanufacturing technology. In the considered market, an OEM and an IR compete by respectively selling new and remanufactured products. To remanufacture used products manufactured by the OEM, the IR can obtain remanufacturing technology by either licensing from the OEM through a royalty licensing contract or self-developing at a fixed R&D cost in-house. This study investigated how the market competition, the IR's optimal quality decision for remanufactured products, and the IR's remanufacturing strategy are affected by the royalty licensing contract between the OEM and the IR. On the one hand, the royalty licensing contract will always induce the OEM and the IR to increase their sales price for new and remanufactured products. However, the OEM will always raise its sales price by a higher degree than that of the IR. Hence, the competition between new and remanufactured products becomes fiercer when there is a royalty licensing contract. In addition, the royalty licensing can always induce the IR to produce remanufactured products at a high-quality level which means that the licensing contract has a competition-intensifying effect on product quality. As such, compared with benchmark case without licensing, remanufactured product will become more competitive with the royalty licensing since remanufactured product will be sold at a lower price but with a higher quality. Even so, a royalty licensing contract is still mutually acceptable and becomes a win-win solution for the OEM and the IR.

This study also examined the robustness of the analytical results by considering three extensions: (a) when the licensing can increase customers' willingness to pay for remanufactured products, (b) when the IR's optimal quality decisions are endogenous and continuous, and (c) when the OEM can strategically determine the optimal royalty fee after observing the IR's optimal quality choice for remanufactured products. The three extensions show that the analytical results from the main analysis remain qualitatively the same. In addition, several new insights are found from the extensions. In the first extension when customers have a higher willingness to pay for remanufactured products after licensing, it is found that the competition between new and remanufactured products may be alleviated as the OEM will strategically decrease the sales price for new products in response to the improvement of customers' willingness to pay. In the third extension when the OEM determines the optimal royalty fee after observing the IR's optimal quality choice, it is found that the royalty licensing contract can also motivate the IR to strategically remanufacture the used products at a low-quality level.

7.2. Managerial implications

From a theoretical perspective, this study uses a game-theoretical method that underpins the strategic implications of intercompetitor licensing of remanufacturing technology between an OEM and an IR. To characterize the impact of intercompetitor licensing on market competition and equilibrium, customers' different valuation for new and remanufactured products, production cost, unit royalty fee, fixed cost incurred for self-developing technology, and quality level of remanufactured products are incorporated into the proposed model. The analytical results not only characterize OEM's and IR's optimal responses in different licensing cooperation scenarios but also identify the conditions under which a mutually beneficial licensing contract is acceptable for both the OEM and the IR.

From a practical perspective, this study proposes how the OEM, and the IR should make licensing cooperation decision aiming to achieve a win-win solution. Conventional wisdom suggests that the OEM should not license its manufacturing technology to a competitor IR if such licensing can significantly decrease the IR's production cost and make the competitor's product more competitive in the market [11]. In addition, the IR should not seek licensing cooperation from the OEM if the total paid royalty fee for licensing is higher than the incurred fixed R&D cost of self-developing the technology. This study reveals that a royalty licensing contract can be mutually acceptable between the OEM and the IR in a wide range of parameter regions. This result is important for the managers who want to engage in the remanufacturing business. For the OEM, the result shows that licensing its remanufacturing technology at a low royalty fee may still be beneficial. For the IR, the result shows that seeking technology licensing may be more profitable even when the total paid royalty fee is higher than the cost of self-developing the technology. Strategic implications of royalty licensing on market competition, remanufacturing production strategy, and remanufacturing quality strategy should be carefully considered before making strategic decisions on remanufacturing and licensing cooperation.

In addition, this study also provides potential explanation for current industry practice. For example, towards the fast development of remanufacturing industry, Apple's strategy has evolved from non-licensing to licensing and providing necessary technology and know-how to its competitor IR (i.e., Ifengpai) to conduct remanufacturing using authorization [13]. After gaining authorization from Apple, many customers swarmed to purchase the "authorized iPhone" from Ifengpai which even crashed its website at one time [54]. Licensing cooperation certainly improves customers' valuation for remanufactured products, alleviates customers' uncertainty about the quality of remanufactured products, and makes remanufactured products more competitive in the market which in turn would deepen cannibalization effect between new and remanufactured products. As such, Apple would face a great challenge in its primary market as customers with limited budget will not buy new products if they had already purchased remanufactured products. However, the final licensing strategy of Apple is consistent with our model analysis which shows that there exists a wide range of parameter regions where licensing cooperation is a win-win solution for both the OEM and the IR as long as the royalty fee is charged at a reasonable level. Though the details of the terms of licensing cooperation between Apple and Ifengpai are private information, our study provides a possible alternative explanation for why OEMs may be willing to license their technology to a competitive IR, and why IR may be incentivized to accept the licensing authorization.

7.3. Limitations and future research

This study has several limitations that deserve further consideration for future research. First, the analytical models assumed that the number of products remanufactured for sale is always equal to the number of cores that can be collected from the market. This assumption is reasonable in the partial collection scenario (i.e., remanufacturing strategy *R1*) where the IR can always collect used products based on customers' demand for remanufactured products. However, this assumption may be invalid in the full collection scenario (i.e., remanufacturing strategy *R2*) where the IR collects and remanufactures all the used products as not all collected cores can be remanufactured or a large remanufacturing cost will be incurred if the IR chooses to remanufacture these items [55]. Therefore, it will be very interesting to relax this assumption and incorporate remanufacturing rate into consideration. Second, it was assumed that the OEM determines the royalty fee in the royalty licensing contract. In practice, the royalty fee agreed on in licensing contract depends on the relative bargaining power of the OEM and the IR. Hence, the royalty fee may also be determined by the IR if it is the leader in the licensing cooperation [14]. In this case, a Nash bargaining game should be adopted on the royalty fee decision process. Third, customers' demand for new and remanufactured products are strictly derived from customers' utility without considering customers' uncertainty. In fact, the launch of the remanufactured products may face more uncertainties in practice as customers are uncertain about the real quality of the remanufactured products. Therefore, it will also be of practical and theoretical interests to investigate the impact of customers' uncertainty on the OEM's and IR's optimal decisions, market equilibrium, the IR's quality decision, and licensing cooperation decision. Finally, the research assumes that all events transpire within a single period. This assumption is valid in that it considers the average status of a supply chain when similar products are introduced to the market repeatedly. However, for the first introduction of a product, there exists a period when the OEM only sells new products before the period when new and remanufactured products coexist in the market. Therefore, examining the OEM's and IR's licensing cooperation decision in a multi-period setting will be of great interest.

Acknowledgements

The authors declare no conflict of interest in this research. The authors would like to thank the editors and reviewers for their constructive comments which help improve this article.

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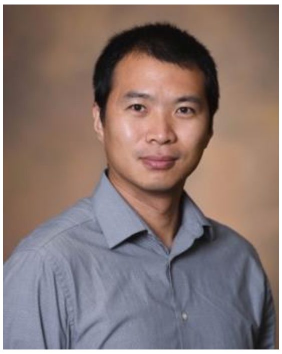

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