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HOW DOES THE POWER STRUCTURE AFFECT THE ACQUISITION PRICE AND INVENTORY DECISIONS IN THE REVERSE SUPPLY CHAIN

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Abstract. With growing concerns about environmental sustainability, reverse supply chains play a crucial role in recycling, remanufacturing, and reducing waste. Investigating the power structure's impact on decisions related to acquisition prices and inventory management can provide insights into the integration of sustainable practices. This study analyzes a reverse supply chain with a supplier and a remanufacturer, in which the supplier provides the remanufacturer with sorted used cores. We investigate the acquisition pricing and inventory decisions under different power structures (supplier-led Stackelberg model, remanufacturer-led Stackelberg model) through game theory analysis. We first establish the centralized model to explore optimal acquisition decisions and profit of the total system. Then we evaluate the acquisition quantity, wholesale prices, the profit of supplier and remanufacturer in the supplier-led model and in the remanufacturer-led model. Finally, the impact of power structure on the performance of supplier and remanufacturer are explored by numerical analysis, as well as the supply chain system. Our significant findings show that (i) the total profit of the supplier-led and remanufacturer-led reverse supply chain are less than the centralized model due to the double marginalization; (ii) the remanufacturer-led reverse supply chain is superior to the supplier-led model reverse supply chain; (iii) the selected grades in the supplier-led model is proved the same as that in the remanufacturer-led model, which could not been affected by the wholesale price; (iv) the greater the inventory risk (the uncertainty in demand), the greater the profit share for the remanufacturer (supplier) in the supplier-led (remanufacturer-led) model.

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1. Introduction

Remanufacturing is a green production mode through recycling waste products to reduce the mining of raw materials, save the cost of enterprises and reduce carbon emissions [1–3]. Remanufacturing activities are much more difficult to operate than traditional manufacturing because its raw materials come from recycled products with varying quality [4]. For this reason, more refined management is needed. Relevant enterprises and scholars have made a lot of attempts and researches from the aspects of original product design [5, 6], rental and sale mode selection [7], product pricing [8, 9], acquisition and production management [10–12], recycling network

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construction [13,14], channel selection [15,16], reverse supply chain network design [17–19], consumer behavior [20,21], preservation technology [22,23] and government policy [24] and so on.

As proposed by, classification of recycled products before remanufacturing can effectively improve operational efficiency and reduce costs, which has been continuously verified and discussed [25–30]. In practice, the price of the cores is set either by the manufacturer or by the retailer. For instance, Aihuishou acts as a supplier and the price setter, sorting and selling used cellphones or components to other remanufacturers or sales agents. Meanwhile, the vehicle manufacturer, Toyota acts as a remanufacturer and the price setter in its remanufacturing business. There are many studies on the operational activities of remanufacturing mode, however, few analyses are conducted when considering the influence of the different power structures.

Therefore, this study aims to investigate what factors would affect the acquisition quantity and pricing decisions of different grades of cores, and how does power structure affect the profits of supplier, remanufacturer and the supply chain system. In supplier-led (remanufacturer-led) model, the supplier (remanufacturer) first sets the wholesale price of each grade, and the remanufacturer (supplier) chooses his optimal acquisition quantity of each grade according to the processing (acquisition) price and wholesale price given by the supplier (remanufacturer). The ownership of the cores inventory belongs to the remanufacturer (supplier) before the demand is realized in supplier-led (remanufacturer-led) model, which means the remanufacturer (supplier) bears full inventory risk. This research contributes by examining the impact of power structures on acquisition prices and inventory decisions in the reverse supply chain, specifically in the context of quality grading, providing valuable insights for optimizing decision-making processes in quality-driven environments.

The following contents are as follows: The related literature is reviewed in Section 2. The supplier-led Stackelberg model, remanufacturer-led Stackelberg model and centralized model are established in Section 3. The acquisition quantity and pricing, and the profit of the supplier, remanufacturer and supply chain system under different power structures are discussed in Section 4. Section 5 presents a case study and sensitivity analysis. We summarize the conclusions and highlights possible directions in Section 6.

2. Literature review

We review the most relevant literature in three streams: core acquisition management with quality grading, the effect of power structure on the reverse supply chain and joint pricing and inventory decisions of remanufacturing system.

2.1. Core acquisition management with quality grading

Core acquisition is one of the most critical activities in remanufacturing activities, which is also the reason why it is more complicated than traditional manufacturing activities. Generally, remanufacturing enterprises not only face the same problems as traditional manufacturing enterprises, such as the uncertainty of demand side and supply interruption, but also the uncertainty of the quality, quantity and collection time of used cores. Identified quality-based categorization is most effective for remanufacturing. Ferguson *et al.* [25] proved quality grading is an effective way to deal with uncertainty about the quality of returned products. Teunter and Flapper [31] and Yang *et al.* [32] studied acquisition and remanufacturing decisions in presence of uncertain core quality. Hahler and Fleischmann [26] presented a strategic grading in the product acquisition process for a reverse Supply Chain. Sun *et al.* [30] optimized acquisition lot size and remanufacturing sequence with considering the cores are sorted into different quality grades before remanufacturing. Yang *et al.* [33] investigated the joint acquisition and remanufacturing problem, where the quality of cores has a discrete empirical distribution. Mutha *et al.* [34] discussed whether a third party remanufacturer (3PR) should acquire sorted cores or sorted cores. Subsequently, they analysed the transactions between a supplier and a 3PR, and explored optimal quantity of each grade should to acquire through Stackelberg game framework [35]. More recently, Mishra *et al.* [36], Bulmuş *et al.* [37], Clottey and Benton [38] and Lechner and Reimann [39] discussed the acquisition decisions when there cores are sorted into different grades. Furthermore, Mutha and Bansal [40] optimized the number

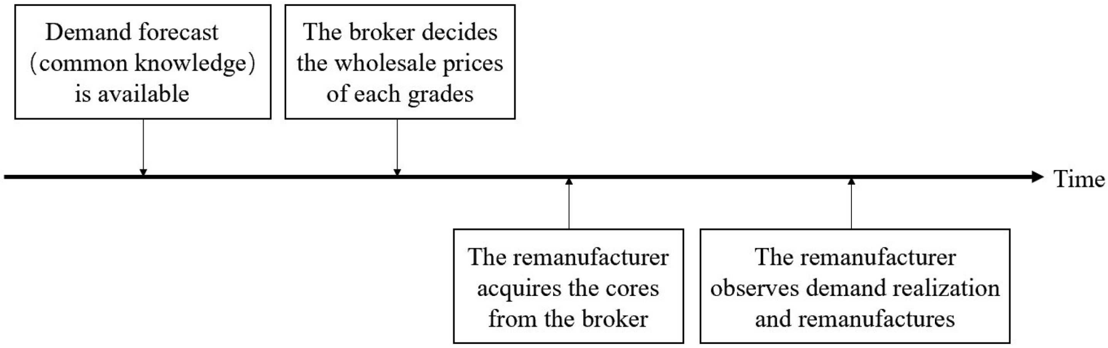

FIGURE 1. Sequence of supplier-led model.

of grades, they pointed out that the optimal number of grades depends on the expected production costs, retail prices and demand uncertainty.

2.2. Pricing decision in the reverse supply chain

There are many literatures which explored the pricing decisions. Some focused on the pricing of finished serviceable products [12, 41–47], while others considered the price of recycled goods [48–51]. Specially, some literatures obtained the optimal the acquisition price based on the quality grading. For example, Bulmuş *et al.* [37] established a model for determining the pricing when the quality of cores are various. Mutha *et al.* [35] developed a Stackelberg game to analyze a supplier sells sorted cores to a remanufacturer. The results show that not all grades will be selected, which depends on the marginal profit of each grade and uncertainty of demand.

2.3. The effect of power structure on the reverse supply chain

In terms of the literature consider the power structure on the reverse supply chain, the research purpose is usually to analyze the decision order of participants and the corresponding optimal decision, profit distribution and system efficiency, and some studies extend to the design of distribution mechanism design. Some studies focused on the transactions between a collector and a remanufacturer [52–54], some focused on the transactions between a remanufacturer and a retailer [55–59], and some focused on three-level supply chain which consists of a retailer, a collector, and a manufacturer [60, 61]. However, there is no research involved in quality grading, which is one of the most prominent features of recycled parts used in remanufacturing, which is also one of the focuses of this paper.

This paper is most relevant to Mutha *et al.* [35], the main differences are as follows: First, we not only study the assortment and the prices of each grades, but also pay attention to the profit distribution of supplier, remanufacturer and the reverse supply chain, while Mutha *et al.* [35] only focuses on choosing the assortment and the prices of the grades; second, we construct the supplier-led model, remanufacturer-led model, and centralized model to explore the impacts of power structure, while Mutha *et al.* [35] only optimizes the assortment and pricing strategies under the supplier-led structure.

3. Modeling framework

We consider a supplier offers $i = 1, 2, \ldots, n$ different grades of cores to a remanufacturer. The remanufacturer faces a stochastic demand with cumulative density function $F(\bullet)$ and probability density function $f(\bullet)$. In the supplier-led Stackelberg structure, the supplier decides the price of each grade. In the remanufacturer-led Stackelberg structure, the remanufacturer decides the price of each grade. The sequences of events are shown in Figures 1 and 2.

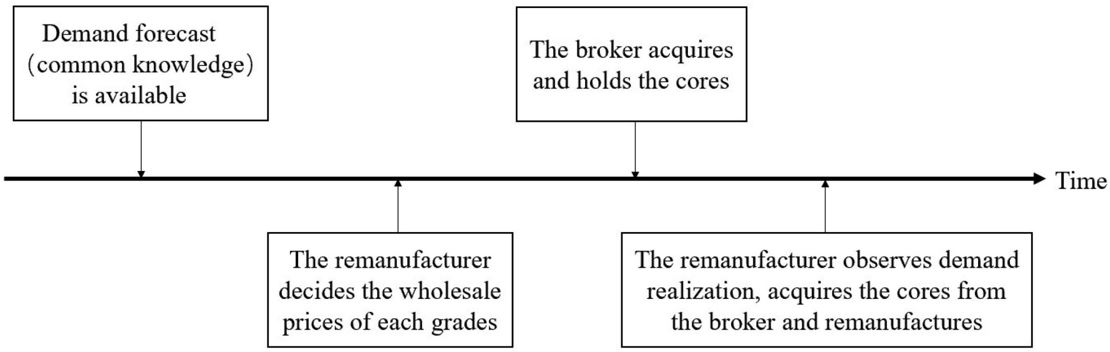

FIGURE 2. Sequence of remanufacturer-led model.

TABLE 1. Parameters and definitions.

Symbol	Definition
i	Quality category, $i = 1(best), 2, \cdots, n(worst)$
Q_i	Quantity of grade i acquired by the decision maker, where Q is the total quantity of cores acquired, $Q = \sum_{i=1}^{n} Q_i$, and $\boldsymbol{Q}$ is the vector of acquisition quantity, $\boldsymbol{Q} = [Q_1, Q_2, \cdots, Q_n]$
r_i	Processing cost for per quality-i core
w_i	Wholesale price per quality-i core, and $\boldsymbol{w}$ is the vector of wholesale price, $\boldsymbol{w} = [w_1, w_2, \cdots, w_n]$
c_i	Acquisition cost per quality-i core, and $\boldsymbol{c}$ is the vector of acquisition cost, $\boldsymbol{c} = [c_1, c_2, \cdots, c_n]$
p	Sale price per remanufactured product
D	Demand quantity
c	Superscript of the centralized model
b	Superscript of the supplier-led model
r	Superscript of the remanufacturer-led model

The parameters are shown in Table 1.

Section 3.1 shows the centralized model. Section 3.2 demonstrates the different results when it is under a supplier-led model. Then we evaluate the acquisition quantity, wholesale prices, the profit of supplier and remanufacturer in the remanufacturer-led model in Section 3.3.

3.1. Centralized model

The centralized model maximizes the sum profit of the supplier and remanufacture. The acquisition quantity $\boldsymbol{Q}^c = [Q_1^c, Q_2^c, \cdots, Q_n^c]$ is the only decision variables. It is a two-stage problem. In Stage 1, the central decision-maker acquires Q_i units of grade i. In Stage 2, the remanufacturer converts cores into remanufactured products to meet the demand after the demand is realized. A lower quality grade core is cheaper to acquire, $c_1 > c_2 > \cdots > c_n$, but is more expensive to remanufacture to a remanufactured product, $r_1 < r_2 < \cdots < r_n$. Therefore, the remanufacturer processes the cores in order of quality from highest to lowest.

The supply chain's optimal profit can be formulated as follows:

$$\text{Stage 1}: \max_{Q^c} \Pi\left(\boldsymbol{Q}^c\right) = -\sum_i c_i Q_i^c + E_D\left(\theta\left(D \mid \boldsymbol{Q}^c\right)\right) \tag{1}$$

$$\text{Stage 2}: \theta\left(D \mid \boldsymbol{Q}^c\right) = \max_{g_i \geq 0}\left[\sum_i\left(p - r_i\right) g_i\right] \tag{2}$$

$$\text{such that } \sum_i g_i \leq D \tag{3}$$

$$g_i \leq Q_i^c \quad \forall i. \tag{4}$$

The objective function in equation (2) represents the revenue, equations (3) and (4) are the restriction of realized demand and the available supply. For realized demand D, we can get Proposition 1.

Proposition 1. *The supply chain's optimal profit of the centralized model is jointly concave in* $\boldsymbol{Q}^c$.

Let consider any three grades, i, $i+1$ and $i+2$. At inventory level $\sum_{j=1}^{i+1} Q_j^c$, the marginal benefit of the grade $i+1$ and grade $i+2$ is equal and the remanufacturer will acquire grade $i+2$ instead of grade $i+1$, $(p - r_{i+1})\,\bar{F}(\sum_{j=1}^{i+1} Q_j^c) - c_{i+1} = (p - r_{i+2})\,\bar{F}(\sum_{j=1}^{i+1} Q_j^c) - c_{i+2}$, that is, $\bar{F}(\sum_{j=1}^{i+1} Q_j^c) = \frac{c_{i+1}-c_{i+2}}{r_{i+2}-r_{i+1}}$. If the acquisition quantity of $i+1$,Q_{i+1} is not zero, then $\bar{F}(\sum_{j=1}^{i} Q_j^c) > \bar{F}(\sum_{j=1}^{i+1} Q_j^c)$, that is, $\frac{c_i - c_{i+1}}{r_{i+1}-r_i} > \frac{c_{i+1}-c_{i+2}}{r_{i+2}-r_{i+1}}$. Similarly, the remanufacturer will acquire grade n instead of grade $n-1$ if $\frac{c_{n-1}-c_n}{r_n - r_{n-1}} > \frac{c_n}{p - r_n}$. If there is grade k, $\left(\frac{c_{k-1}-c_k}{r_k - r_{k-1}}\right) < \left(\frac{c_k - c_{k+1}}{r_{k+1}-r_k}\right) > \left(\frac{c_k - c_{k+1}}{r_{k+1}-r_k}\right)$, then the supplier does not order a positive amount of grade k.

Based on above analysis, we can get the acquisition quantity in the centralized model.

Proposition 2. *The optimal acquisition quantity for each grade in the centralized model is as follows:*

$$Q_1^{c^*} = \max\left\{\bar{F}^{-1}\left(\frac{c_1 - c_2}{r_2 - r_1}\right), 0\right\} \tag{5}$$

$$Q_i^{c^*} = \max\left\{\bar{F}^{-1}\left(\frac{c_i - c_{i+1}}{r_{i+1} - r_i}\right) - \bar{F}^{-1}\left(\frac{c_{i-1} - c_i}{r_i - r_{i-1}}\right), 0\right\} \quad \forall i = 2, \cdots, n-1 \tag{6}$$

$$Q_n^{c^*} = \max\left\{\bar{F}^{-1}\left(\frac{c_n}{p - r_n}\right) - \bar{F}^{-1}\left(\frac{c_{n-1} - c_n}{r_n - r_{n-1}}\right), 0\right\}. \tag{7}$$

Proposition 2 gives the remanufacturer's best acquisition quantity for each grade, which is depend on the vector of acquisition costs $\boldsymbol{c}$, the vector of processing cost $\boldsymbol{r}$ and sale price p.

3.2. Supplier-led model

In the supplier-led model, the supplier decides the prices (w_i^b), the remanufacturer then decides the acquisition quantities of grade i before demand is realized, and converts cores into remanufactured products in order of quality from highest to lowest after he observes the demand.

3.2.1. Remanufacturer's problem in the supplier-led model

The remanufacturer problem in the supplier-led model is similar to that supply chain system in the centralized model, except that the system's acquisition prices are $\boldsymbol{c}$ in the centralized model, whereas the remanufacturer's acquisition prices are $\boldsymbol{w^b}$ in the supplier-led model, which is given by the supplier. The remanufacturer's optimal profit in the supplier-led model can be formulated as follows:

$$\text{Stage 1: } \max_{Q^b} \pi_R^b\left(\boldsymbol{Q}^b\right) = -\sum_i w_i^b Q_i^b + E_D\left(\theta\left(D \mid \boldsymbol{Q}^b\right)\right) \tag{8}$$

$$\text{Stage 2: } \theta\left(D \mid \boldsymbol{Q}^b\right) = \max_{g_i \geq 0}\left[\sum_i (p - r_i)\, g_i\right] \tag{9}$$

$$\text{such that } \sum_i g_i \leq D \tag{10}$$

$$g_i \leq Q_i^b \quad \forall i. \tag{11}$$

Similarly, we can get Propositions 3 and 4.

Proposition 3. *The profit of the remanufacturer in the supplier-led model is jointly concave in* $\boldsymbol{Q}^b$.

Proposition 4. *The remanufacturer's optimal acquisition quantity for each grade in the supplier-led model is specified as follows:*

$$Q_1^{b^*} = \max\left\{\bar{F}^{-1}\left(\frac{w_1^b - w_2^b}{r_2 - r_1}\right), 0\right\} \tag{12}$$

$$Q_i^{b^*} = \max\left\{\bar{F}^{-1}\left(\frac{w_i^b - w_{i+1}^b}{r_{i+1} - r_i}\right) - \bar{F}^{-1}\left(\frac{w_{i-1}^b - w_i^b}{r_i - r_{i-1}}\right), 0\right\} \quad \forall i = 2, \cdots, n-1 \tag{13}$$

$$Q_n^{b^*} = \max\left\{\bar{F}^{-1}\left(\frac{w_n^b}{p - r_n}\right) - \bar{F}^{-1}\left(\frac{w_{n-1}^b - w_n^b}{r_n - r_{n-1}}\right), 0\right\}. \tag{14}$$

3.2.2. Supplier's problem in the supplier-led model

In the supplier-led model, the supplier decides the collection quantity Q_i^b and the wholesale prices (w_i^b) she offers to the remanufacturer. Based on the Proposition 4, the supplier's optimal profit can be obtained as follows:

$$\max_{w^b \geq 0} \pi_B^b\left(\boldsymbol{w}^b\right) = \max_{w^b \geq 0}\left[\sum_{i=1}^{n}\left(w_i^b - c_i\right) Q_i^b\right] \tag{15}$$

$$\text{such that } Q_1^b = \max\left\{\bar{F}^{-1}\left(\frac{w_1^b - w_2^b}{r_2 - r_1}\right), 0\right\} \tag{16}$$

$$Q_i^b = \max\left\{\bar{F}^{-1}\left(\frac{w_i^b - w_{i+1}^b}{r_{i+1} - r_i}\right) - \bar{F}^{-1}\left(\frac{w_{i-1}^b - w_i^b}{r_i - r_{i-1}}\right), 0\right\}, \quad \forall i = 2, \cdots, n-1 \tag{17}$$

$$Q_n^b = \max\left\{\bar{F}^{-1}\left(\frac{w_n^b}{p - r_n}\right) - \bar{F}^{-1}\left(\frac{w_{n-1}^b - w_n^b}{r_n - r_{n-1}}\right), 0\right\}. \tag{18}$$

The optimal wholesale price can be obtained from equations (16) to (18), which can be express by equation (19).

$$w_i^b = (p - r_n)\, \overline{F}\left(\sum_{j=1}^{n} Q_j^b\right) + \sum_{j=i}^{n-1}\left[(r_{j+1} - r_j)\, \overline{F}\left(\sum_{j=1}^{k} Q_j^b\right)\right]. \tag{19}$$

Substituting the w_i^b into equation (15), we obtain the supplier's problem as follows.

$$\max_{\boldsymbol{Q}^b \geq 0} \pi_B^b\left(\boldsymbol{Q}^b\right) = (p - r_n)\, \overline{F}\left(\sum_{j=1}^{n} Q_j^b\right) \sum_{j=1}^{n} Q_j^b + \sum_{i=1}^{n-1}\left[(r_{i+1} - r_i)\, \overline{F}\left(\sum_{j=1}^{i} Q_j^b\right) \sum_{j=1}^{i} Q_j^b\right] - \sum_{j=1}^{n} c_j Q_j^b. \tag{20}$$

Consequently, the acquisition quantity of the supplier can be obtained according to Proposition 5.

Proposition 5. *The optimal acquisition quantity* $\mathbf{Q}^{b^*}$ *in the supplier-led model is unique and satisfies the following conditions:*

$$Q_j^{b^*} := (p - r_n)\left[\bar{F}\left(\sum_{j=1}^{n} Q_j^{b^*}\right) - f\left(\sum_{j=1}^{n} Q_j^{b^*}\right)\sum_{j=1}^{n} Q_j^{b^*}\right] + \sum_{k=i}^{n-1}(r_{k+1} - r_k)\left[\bar{F}\left(\sum_{j=1}^{k} Q_j^{b^*}\right) - f\left(\sum_{j=1}^{k} Q_j^{b^*}\right)\sum_{j=1}^{k} Q_j^{b^*}\right] - c_i = 0, \quad i = 1, 2, \cdots, n-1 \tag{21}$$

$$Q_n^{b^*} := (p - r_n)\left[\bar{F}\left(\sum_{j=1}^{n} Q_j^{b^*}\right) - f\left(\sum_{j=1}^{n} Q_j^{b^*}\right)\sum_{j=1}^{n} Q_j^{b^*}\right] - c_n = 0. \tag{22}$$

3.3. Remanufacturer-led model

The remanufacturer-led model is a pull supply chain. The remanufacturer decides the wholesale prices w_i but does not prebook cores. The supplier chooses the acquisition quantities of each grade at a per unit costs c_i before demand is realized. The remanufacturer orders cores and remanufactures them to meet the realized demand, in descending order of profit margin.

3.3.1. Supplier's problem in the remanufacturer-led model

The analysis of supplier in the remanufacturer-led system is also similar to that in the centralized system, except that the supply chain system's expected marginal profits of grade i in the stage 2 are $p - r_i$ in the centralized model, whereas the supplier's expected marginal profits of grade i in the stage 2 are w_i in the remanufacturer-led model, which is given by the remanufacturer.

The supplier optimal profit can be formulated as follows

$$\text{Stage 1: } \max_{\boldsymbol{Q}^r} \pi_B^r(\boldsymbol{Q}^r) = -\sum_i c_i Q_i^r + E_D\left(\theta\left(D \mid \boldsymbol{Q}^r\right)\right) \tag{23}$$

$$\text{Stage 2: } \theta(D \mid \boldsymbol{Q}^r) = \max_{g_i \geq 0}\left[\sum_i w_i^r g_i\right] \tag{24}$$

$$\text{such that } \sum_i g_i \leq D \tag{25}$$

$$g_i \leq Q_i^r \quad \forall i. \tag{26}$$

Similarly, we can get Propositions 6 and 7.

Proposition 6. *The profit of the supplier in the remanufacturer-led model given is jointly concave in* $\boldsymbol{Q}^r$*.*

Proposition 7. *The supplier's optimal acquisition quantity for each grade in the remanufacturer-led model is specified as follows:*

$$Q_1^{r^*} = \min\left\{\overline{F}^{-1}\left(\frac{c_1 - c_2}{w_1^r - w_2^r}\right), 0\right\} \tag{27}$$

$$Q_i^{r^*} = \max\left\{\overline{F}^{-1}\left(\frac{c_i - c_{i+1}}{w_i^r - w_{i+1}^r}\right) - \overline{F}^{-1}\left(\frac{c_{i-1} - c_i}{w_{i-1}^r - w_i^r}\right), 0\right\} \quad \forall i = 2, \cdots, n-1 \tag{28}$$

$$Q_n^{r^*} = \max\left\{\overline{F}^{-1}\left(\frac{c_n}{w_n^r}\right) - \overline{F}^{-1}\left(\frac{c_{n-1} - c_n}{w_{n-1}^r - w_n^r}\right), 0\right\}. \tag{29}$$

Once the optimal quantities $Q_j^{r^*}$ are obtained, the optimal selling prices can be obtained by equation

$$w_i^{r^*} = \frac{c_n}{\bar{F}\left(\sum_{j=1}^{n} Q_j^{r^*}\right)} + \sum_{k=i}^{n-1}\left[\frac{(c_k - c_{k+1})}{\bar{F}\left(\sum_{j=1}^{k} Q_j^{r^*}\right)}\right] \quad \forall i = 1, 2, \cdots, n-1. \tag{30}$$

3.3.2. Remanufacturer's problem in the remanufacturer-led model

In the remanufacturer-led model, the remanufacturer maximizes her profit by deciding the wholesale prices (w_i^r) in anticipating to the supplier's acquisition decision Q_i^r. The remanufacturer's problem can be formulated as follows:

$$\max_{\boldsymbol{Q}^r \geq \boldsymbol{0}} \pi_R^r(\boldsymbol{Q}^r) = \max_{\boldsymbol{g}_i \geq 0}\left[\sum_i \left(p - r_i - w_i^r(\boldsymbol{Q}^r)\right)\boldsymbol{g}_i\right] \tag{31}$$

$$\text{such that} \quad \sum_i g_i \leq D \tag{32}$$

$$g_i \leq Q_i^r \quad \forall i. \tag{33}$$

As mentioned before, the remanufacturer will convert cores into remanufactured products in order of quality from highest to lowest after the demand is realized with assumption that the better the quality of the cores, the higher the marginal profit. Hence, we can rewrite the remanufacturer's objective function equations (31–33) as follows:

$$\max_{Q^r \geq 0} \pi_R^r(\boldsymbol{Q}^r) = \sum_{i=1}^{n}\left(p - r_i - w_i^r(\boldsymbol{Q}^r)\right)\min\left(\left(D - \sum_{j=1}^{i-1} Q_j^{r^*}\right)^+, Q_i^{r^*}\right). \tag{34}$$

Substituting (w_i^r) into equation (34), the optimal acquisition quantity can be chartered by Proposition 8.

Proposition 8. *The optimal acquisition quantity $\boldsymbol{Q}^{r^*}$ in the remanufacturer-led model is satisfies the following condition:*

$$Q_n^{r^*} := (p - r_n)\,\overline{F}\left(\sum_{j=1}^{n} Q_j^r\right) - \frac{c_n h\left(\sum_{j=1}^{n} Q_j^r\right)}{\overline{F}\left(\sum_{j=1}^{n} Q_j^r\right)} S\left(\sum_{j=1}^{n} Q_j^r\right) - c_n = 0 \tag{35}$$

$$\begin{aligned} Q_j^{r^*} := {} & (p - r_n)\overline{F}\left(\sum_{j=1}^{n} Q_j^r\right) - \frac{c_n h\left(\sum_{j=1}^{n} Q_j^r\right)}{\overline{F}\left(\sum_{j=1}^{n} Q_j^r\right)} S\left(\sum_{j=1}^{n} Q_j^r\right) - c_i \\ & + \sum_{k=i}^{n-1}\left[(r_{k+1} - r_k)\,\overline{F}\left(\sum_{j=1}^{k} Q_j^r\right) - \frac{(c_k - c_{k+1})\,h\left(\sum_{j=1}^{k} Q_j^r\right)}{\overline{F}\left(\sum_{j=1}^{k} Q_j^r\right)} S\left(\sum_{j=1}^{k} Q_j^r\right)\right] = 0, \quad i = 1, 2, \cdots, n-1 \end{aligned} \tag{36}$$

where $S(Q) = Q - \int_0^Q F(x)\,\mathrm{d}x$.

Now, we have established acquisition model and analyzed the optimal acquisition and pricing policies under different power structures. Next, we will explore the effect of power structure on acquisition and pricing decisions through comparative analysis.

4. The effect of power structure

According to the above analysis, the remanufacturer bears the inventory risk in the supplier-led model, whereas the supplier bears the inventory risk in the remanufacturer-led model. We first explore the acquisition quantity of various grades of cores under different power structures, and then explore the profit distribution problem. For the purposes of the following analysis, we first present Lemma 1 [62].

Lemma 1. *For $Q > 0$, $j(Q)h(Q)$ is increasing, where $j(Q) = s(q)/1 - F(q)$ and $h(Q)$ is the hazard rate, $f(q)/1 - F(q)$.*

As demonstrated in Propositions 6 and 8, $\mathbf{Q}^{b^*} = \arg\max \pi_B^b(\mathbf{Q}^b)$, $\mathbf{Q}^{r^*} = \arg\max \pi_R^r(\mathbf{Q}^r)$, where $\mathbf{Q}^b = [Q_1^b, Q_2^b, \cdots, Q_n^b]$, $\mathbf{Q}^r = [Q_1^r, Q_2^r, \cdots, Q_n^r]$, $\frac{\partial \pi_B^b}{\partial Q_i^b}\left(Q_i^{b^*}\right) = 0$ and $\frac{\partial \pi_R^r}{\partial Q_i^r}\left(Q_i^{r^*}\right) = 0$.

In order to figure out the magnitude relationship between $Q_i^{b^*}$ and $Q_i^{r^*}$, $i = 1, 2, \cdots, n-1$, let's begin with the remanufacturer's first-order condition in the remanufacturer-led system $\frac{\partial \pi_R^r}{\partial Q_i^r}\left(Q_i^{b^*}\right)$.

$$\begin{aligned}
\frac{\partial \pi_R^r}{\partial Q_i^r}\left(Q_i^{b^*}\right) &= \left(p - r_n\right)\overline{F}\left(\sum_{j=1}^{n} Q_j^{b^*}\right) - \frac{c_n h\left(\sum_{j=1}^{n} Q_j^{b^*}\right)}{\overline{F}\left(\sum_{j=1}^{n} Q_j^{b^*}\right)} S\left(\sum_{j=1}^{n} Q_j^{b^*}\right) - c_i \\
&\quad + \sum_{k=i}^{n-1}\left[\left(r_{k+1} - r_k\right)\bar{F}\left(\sum_{j=1}^{k} Q_j^{b^*}\right) - \frac{\left(c_k - c_{k+1}\right) h\left(\sum_{j=1}^{k} Q_j^{b^*}\right)}{\bar{F}\left(\sum_{j=1}^{k} Q_j^{b^*}\right)} S\left(\sum_{j=1}^{k} Q_j^{b^*}\right)\right] \\
&= \left(p - r_n\right) f\left(\sum_{j=1}^{n} Q_j^{b^*}\right)\left\{\sum_{j=1}^{n} Q_j^{b^*} j'\left(\sum_{j=1}^{n} Q_j^{b^*}\right) - j\left(\sum_{j=1}^{n} Q_j^{b^*}\right)\right\} \\
&\quad + \sum_{k=i}^{n-1}\left(r_{k+1} - r_k\right) f\left(\sum_{j=1}^{k} Q_j^{b^*}\right)\left[\sum_{j=1}^{k} Q_j^{b^*} j'\left(\sum_{j=1}^{k} Q_j^{b^*}\right) - j\left(\sum_{j=1}^{k} Q_j^{b^*}\right)\right].
\end{aligned}$$

As shown in Lemma 1, $\sum_{j=1}^{n} Q_j^{b^*} j'\left(\sum_{j=1}^{n} Q_j^{b^*}\right) > j\left(\sum_{j=1}^{n} Q_j^{b^*}\right)$, $\sum_{j=1}^{k} Q_j^{b^*} j'\left(\sum_{j=1}^{k} Q_j^{b^*}\right) - j\left(\sum_{j=1}^{k} Q_j^{b^*}\right)$, so $\frac{\partial \pi_R^r}{\partial Q_i^r}\left(Q_i^{b^*}\right) > 0$. Given that π_R^r is unimodal, it follows that $Q_i^{b^*} < Q_i^{r^*}, i = 1, 2, \cdots, n$.

Similarly, we can prove $\frac{\partial \pi_R^r}{\partial Q_i^r}\left(Q_i^{c^*}\right) < 0$. Now, $Q_i^{b^*} < Q_i^{r^*} < Q_i^{c^*}$ is confirmed, $i = 1, 2, \cdots, n$.

Proposition 9. *The optimal acquisition quantity of each grade in the supplier-led system is not greater than that in the remanufacturer-led system, and the optimal acquisition quantity of each grade in the remanufacturer-led system is not greater than that in the centralized system, $Q_i^{b^*} < Q_i^{r^*} < Q_i^{c^*}$, $i = 1, 2, \cdots, n$.*

According to Propositions 1 and 9, we can get Proposition 10.

Proposition 10. *The total optimal profit in the supplier-led system is less than that in the remanufacturer-led system, and the total optimal profit in the remanufacturer-led system is less than that in the centralized system $\prod^{b^*} < \prod^{r^*} < \prod^{c^*}$.*

According to Proposition 10, we can get the following conclusion: first, the overall profit of the supplier-led and remanufacturer-led system are less than the centralized system since the double marginalization; second, the remanufacturer-led reverse supply chain is more efficient than the supplier-led system.

5. Numerical analysis

In this section, we give a case study based on data from ReCellular reported by Mutha *et al.* [35]. The acquisition and processing costs of each grade are $c_i = \{20, 12, 8, 4\}$ (unit: \$) and $r_i = \{3, 12, 20, 30\}$ (unit: \$),

Table 2. The results under different power structures.

	Supplier-led model	Remanufacturer-led model	Centralized model
$\boldsymbol{Q}^*$ (pcs)	$\{55.85, 13.71, 2.06, 5.18\}$	$\{56.49, 17.93, 3.95, 17.38\}$	$\{75.59, 24.41, 5.07, 21.12\}$
$\mathbf{w}^*$ (\$)	$\{62.42, 53.53, 46.05, 36.83\}$	$\{24.64, 15.94, 11.50, 6.85\}$	–
π_B (\$)	3186.98	310.59	–
π_R (\$)	431.76	3876.10	–
$\prod$ (\$)	3618.74	4186.70	6512.27

the selling price of the remanufactured product is $p = \$72$, and the demand follows a normal distribution with $\mu = 100$ (unit: pcs) and $\sigma = 20$ (unit: pcs).

5.1. Results and discussions

As shown in Table 2, the optimal acquisition quantity in the supplier-led model is $Q^{b^*} = \{55.85, 13.71, 2.06, 5.18\}$ and the wholesale price is $w^{b^*} = \{62.42, 53.53, 46.05, 36.83\}$. The supplier's profit is \$3618.98, the remanufacturer's profit is \$431.76 and the total profit is \$3618.74. In the remanufacturer-led model, the optimal acquisition quantity is $Q^{b^*} = \{56.49, 17.93, 3.95, 17.38\}$ and the wholesale price is $w^{b^*} = \{24.64, 15.94, 11.50, 6.85\}$. The supplier's profit is \$310.59, the remanufacturer's profit is \$3876.10 and the total profit is \$4186.70.

As shown in Table 2 and Figure 3, as demonstrated in Propositions 9 and 10, the optimal acquisition quantity (profit) in the supplier-led system is less than that in the remanufacturer-led system, and the optimal acquisition quantity (profit) in the remanufacturer-led system is less than that in the centralized system, $Q_i^{b^*} < Q_i^{r^*} < Q_i^{c^*}$, $\prod^{b^*} < \prod^{r^*} < \prod^{c^*}$, $i = 1, 2, \cdots, n$. On the other hand, the supplier's (remanufacturer's) profit in the supplier-led system (remanufacturer-led system) is more than that in the in the remanufacturer-led system (supplier-led system), since the supplier (remanufacturer) has the first-mover advantage whereas the remanufacturer (supplier) bears the inventory risk in the supplier-led system (remanufacturer-led system).

5.2. Sensitivity analysis

To explore the effect of acquisition cost, let the acquisition cost $\boldsymbol{C}$ gradually increased from 50% to 250%, the results are shown in Table 3. On one hand, the profit of supplier and remanufacturer decrease with the acquisition cost increases. On the other hand, the selected grades are the same in supplier-led model and remanufacturer-led which are determined by the acquisition cost, remanufacturing cost, sale price and demand distribution, but not affected by the wholesale price. At the same time, the number of selected grades decreases because we assume the acquisition cost of different grades increased proportionally results in a greater increase in the lower grade cores. The impact of remanufacturing cost on the results is similar to that of acquisition cost.

To explore the effect of the uncertainty of demand, let σ alter from 0 to 80, the change trend of acquisition quantity under the supplier-led system and remanufacturer-led system are shown in Figures 4 and 5. As σ increases, the acquisition quantity of grade 1 decreases whereas the acquisition quantity of grade 2, 3 and 4 increase. Although grade 1 has the greatest marginal profit $p - c_1 - r_1$, but it has the highest acquisition cost/the greatest inventory risk, which means more initial cost will be lost if it is not used. Therefore, grade 1 are purchased in relatively large quantities when demand variability is relatively small for its greatest marginal profit, and the acquisition quantity of grade 1 will gradually decreases with the increase of demand variability. It's the trade-off between marginal profit and inventory risk. The cores with higher marginal profit will be more attractive when the variability is small, but its inventory risk will be more prominent when the variability is large. Specially, the decision maker will purchase only cores with the highest marginal profit margin when the demand is determined ($\sigma = 0$).

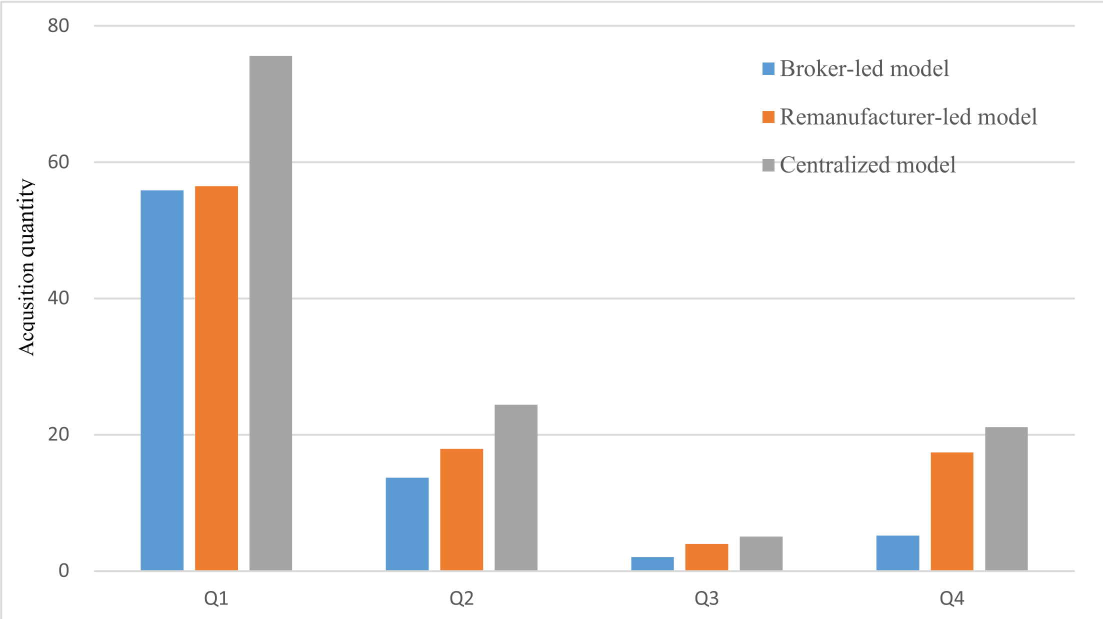

FIGURE 3. The optimal acquisition quantity under different power structures (unit: pcs).

TABLE 3. The results under different acquisition costs.

$\boldsymbol{c}$ (\$)	Power structure	Q^* (pcs)	π_B (\$)	π_R (\$)	$\prod$ (\$)
50% $\boldsymbol{c}$	Supplier-led	$\{70.74, 3.58, 0.86, 2.33\}$	3891.41	531.57	4422.98
	Remanufacturer-led	$\{76.56, 8.53, 2.77, 14.09\}$	355.71	4895.66	5231.37
100% $\boldsymbol{c}$	Supplier-led	$\{55.85, 13.71, 2.06, 5.18\}$	3186.98	431.76	3618.74
	Remanufacturer-led	$\{56.49, 17.93, 3.95, 17.38\}$	310.59	3876.10	4186.70
150% $\boldsymbol{c}$	Supplier-led	$\{0, 62.67, 4.57, 8.82\}$	2713.37	365.50	3078.87
	Remanufacturer-led	$\{0, 64.41, 6.24, 20.98\}$	281.42	3231.70	3513.12
200% $\boldsymbol{c}$	Supplier-led	$\{0, 62.67, 4.57, 8.82\}$	2713.37	365.50	3078.87
	Remanufacturer-led	$\{0, 0, 60.77, 14.53\}$	2323.73	312.29	2636.02
250% $\boldsymbol{c}$	Supplier-led	$\{0, 0, 0, 74.52\}$	2067.49	276.75	2344.23
	Remanufacturer-led	$\{0, 0, 0, 85.7\}$	230.12	2395.28	2625.40

The change trend of profit under the supplier-led system and remanufacturer-led system are shown in Figures 6 and 7, respectively. The supplier's (remanufacturer's) profit and total profit in the supplier-led system (remanufacturer-led system) decreases as the deviation of demand increases, while the remanufacturer's profit increases in the supplier-led system and the supplier's profit first rise and then fall in the remanufacturer-led system. On one hand, as the deviation of demand increases, the increase of uncertainty leads to the decrease of total profit. On the other hand, the remanufacturer (supplier) bears all inventory risk in the supplier-led system (remanufacturer-led system), that is to say, the remanufacturer (supplier) will take on more inventory risk as the deviation of demand increases. In order to maximize its own profit, the supplier (remanufacturer) need to distribute more profits to remanufacturer (supplier) to offset the greater inventory risks. The remanufacturer's (supplier's) profit increases since the compensation profit obtained from supplier (remanufacturer) is greater than the profit loss caused by inventory risk, as shown in Figures 6 and 7. Therefore, for the leader (supplier

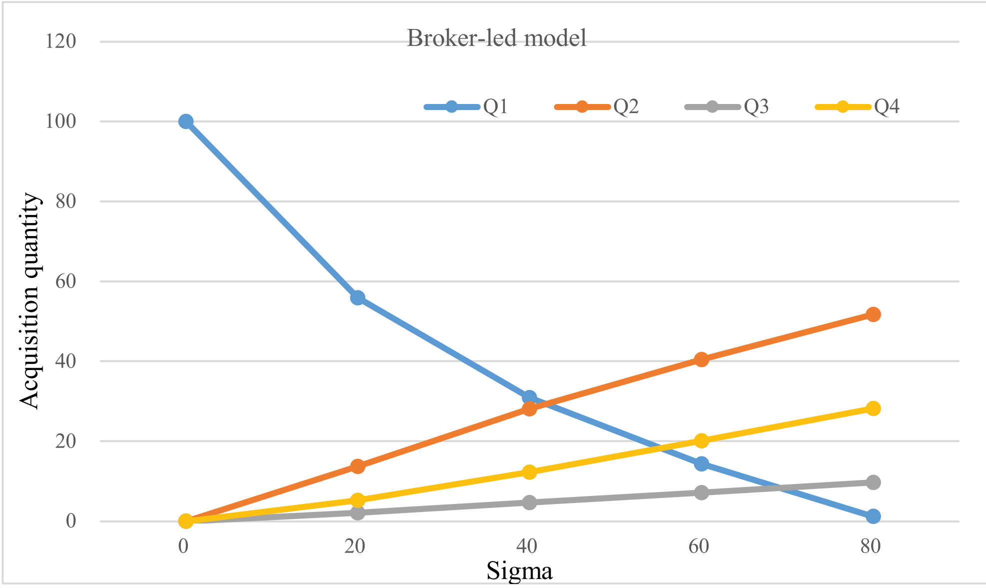

FIGURE 4. The optimal acquisition quantity in the supplier-led model under different standard deviation of demand (unit: pcs).

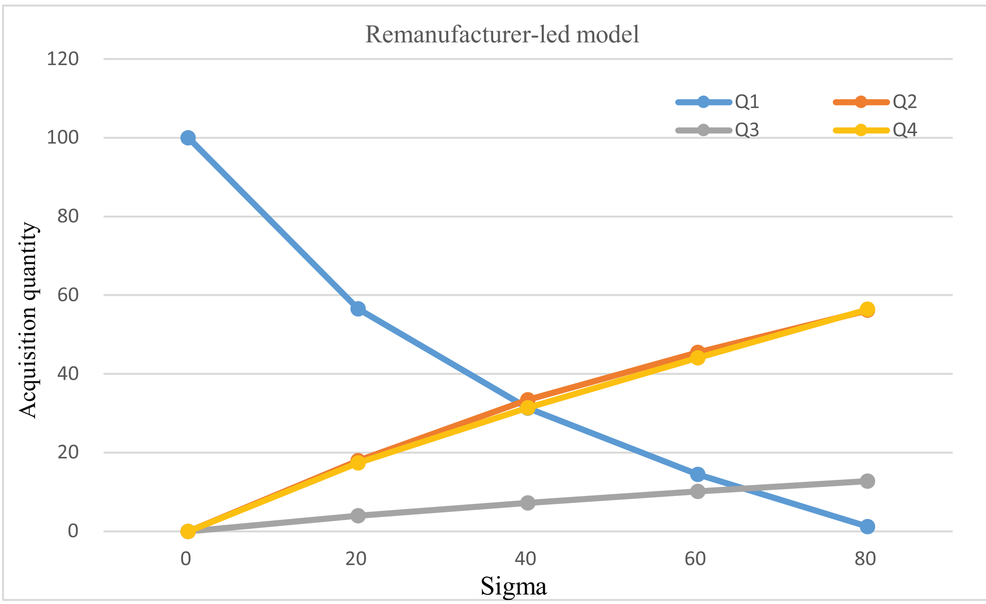

FIGURE 5. The optimal acquisition quantity in the remanufacturer-led model under different standard deviation of demand (unit: pcs).

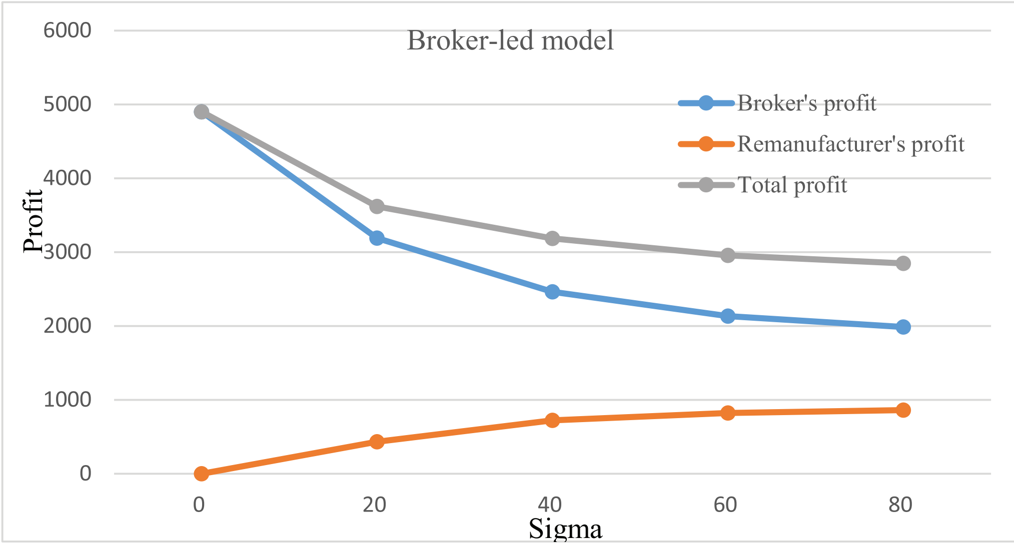

FIGURE 6. The profit in the supplier-led model under different standard deviation of demand (unit: $).

/remanufacturer), it's profit in the supplier-led system/remanufacturer-led system) are bound to decrease as the deviation of demand increases; for the follower (remanufacturer/supplier), it's a trade-off between compensation profit obtained from the leader and loss profit caused by increased inventory risk.

6. Conclusions

Acquisition prices and inventory decisions are strategic elements that directly impact the competitiveness and profitability of the supplier and remanufacturer in the reverse supply chain. Understanding how power structures influence decision-making can help companies develop strategies to enhance efficiency, reduce costs, and improve overall performance. Specifically, the managers can use our findings to optimize acquisition prices in the reverse supply chain. Understanding the power dynamics can help negotiate better terms with suppliers/remanufacturers, potentially reducing acquisition costs, and managers can develop strategies to minimize holding costs and streamline inventory management. In addition, by gaining insights into the impact of power structures on inventory decisions, Managers can leverage this information to strategically choose and nurture partnerships with suppliers, ensuring a reliable and cost-effective reverse supply chain. In this study, we consider a supplier sells assortments of cores to remanufacturers under different power structures. We establish three models: centralized model, Supplier-led model and Remanufacturer-led model, and give analytical solutions for the optimal acquisition quantity and wholesale price of each grade cores. Through comparative analysis and numerical analysis, we find that (i) the overall profit of the supplier-led and remanufacturer-led systems are less than the centralized system since the double marginalization; (ii) the optimal acquisition quantity of each grade in the supplier-led system is not greater than that in the remanufacturer-led system, and the overall profit in the supplier-led system is not greater than that in the remanufacturer-led system accordingly, which means that the remanufacturer-led is more efficient than the supplier-led model; (iii) the selected grades in the supplier-led model is the same as that in the remanufacturer-led model, which is not affected by the wholesale price; (iv) the remanufacturer (supplier) bears all inventory risk in the supplier-led (remanufacturer-led) system, the greater the inventory risk (the uncertainty in demand), the greater the profit share for the remanufacturer (supplier).

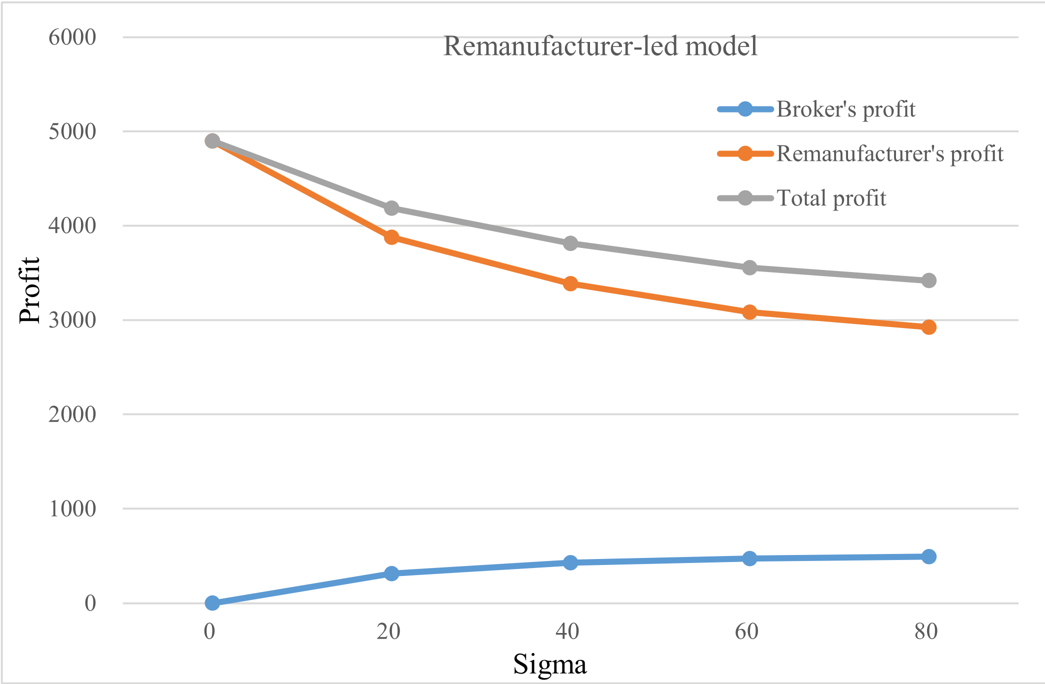

FIGURE 7. The profit in the remanufacturer-led model under different standard deviation of demand (unit: $).

There are several interesting directions for future research. First, the coordination and cooperation mechanism will be explored in future research in order to achieve Pareto optimality. Second, we assumed that the supplier is responsible for purchasing sorted cores to supply to the remanufacturer. In the future, we may continue to explore the optimal decision when the supplier is responsible for both purchasing and sorting.

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Data availability statement

All data generated or analyzed during this study are included in this published article (and its supplementary information files).

Author contribution statement

Hong Sun: Conceptualization, methodology, software, data curation, writing (original draft), visualization, formal analysis, investigation, writing. Yan Li: writing – review and editing.

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