An investigation of original equipment manufacturer’s optimal remanufacturing mode and engagement strategy

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**Abstract**

This study considers an original equipment manufacturer (OEM) who (1) relies on a contract manufacturer (CM) to produce its new products, and (2) engages the CM again or an independent remanufacturer (IR) to perform the remanufacturing operations of branded patented products through either authorization or outsourcing. This study chiefly investigates the optimal remanufacturing engagement strategy (i.e. engage a CM or an IR) and remanufacturing mode (i.e. authorization and outsourcing) that should be taken by an OEM. This paper derives the optimal responses of the three parties (i.e. OEM, CM and IR) by comparing the outcomes of different remanufacturing engagement strategies and remanufacturing modes under two settings, depending on whether the wholesale price is exogenously or endogenously given. The results suggest that the OEM is better off adopting the authorization remanufacturing mode by either working with the CM or the IR when the wholesale price is exogenously given. When the wholesale price is endogenously determined by the CM, the best strategy for the OEM is to work with the IR using the outsourcing approach. The CM and the IR also show different preference between the two modes. The IR or CM which engages in remanufacturing always prefers the outsourcing mode than the authorization mode in the two settings. However, when the CM does not engage in remanufacturing, it is better off adopting the authorization mode when the wholesale price is exogenously given or when the remanufacturing cost is relatively low in the endogenized wholesale price setting.

**Key words:** Production outsourcing; authorization remanufacturing; outsourcing remanufacturing; contract manufacturer; independent remanufacturer

## 1. Introduction

Production outsourcing is a common industry practice because that allows the original equipment manufacturers (OEMs) to focus on their core competencies such as product design and marketing (Kakabadse and Kakabadse 2005). Instead of making products themselves, OEMs can outsource their production to contract manufacturers (CMs) (Bolandifar et al., 2016). In addition, OEMs can also outsource remanufacturing functions to outside contractors (Ferguson and Souza, 2010). Remanufacturing is a process in which used products are disassembled and their parts are repaired before being used in the production of new products (Ferrer et al., 2006). As some parts can be reused repeatedly, the process of remanufacturing is an effective way to protect our environment.

Regarding the engagement of remanufacturing operations, the OEMs have two options: outsourcing remanufacturing and authorization remanufacturing (Zou et al., 2016). The difference between the two remanufacturing modes lies on whether the marketing of the remanufactured products is conducted by the OEM or by the remanufacturer. In the outsourcing setting, the remanufacturer produces whereas the OEM sells the remanufactured products. By contrast, in the authorization setting, the remanufacturer produces and sells the remanufactured products. Concerning the aforementioned options, the OEM can either appoint the original CM (i.e. the manufacturer that produces new products for the OEM), or an independent remanufacturer (IR) to perform the remanufacturing process. This gives rise to a fundamental question: should the OEM outsource the remanufacturing process to the original CM or an IR?

This question has received an increasing deal of attention in business media in recent years. The OEM’s decision regarding whom to cooperate with will not only affect its own profit, but the remanufacturing industry and activity as well. Existing industrial evidence shows that cooperating either with a CM or an IR exists in practice. A number of OEMs, such as Apple, Motorola Mobility, Nokia, Xiaomi and Huawei contract Foxconn (i.e. CM) to produce their smart phones (Troianovski and Clark 2012), while they depend on different operators (i.e. original CM or IR) for remanufacturing. For instance, in the Chinese market, Apple has licensed its original CM Foxconn as an authorized remanufacturer (Apple, 2015), whereas Xiaomi has announced to cooperate with Aihuishou, an IR who specialized in recycling and remanufacturing (Xiaomi, 2015). In the European market, Apple appointed Phobio, a third party, as its remanufacturing partner (Phobio, 2017). A more recent industry trend indicates that OEMs are more inclined to cooperate with IRs to remanufacture their products, such as Huawei, who cooperate with Huishoubao in recycling and remanufacturing (Huawei, 2017). At the same time, OEM can cooperate with its remanufacturing partner by using different remanufacturing modes, that is, outsourcing and authorization. Outsourcing remanufacturing and authorization remanufacturing have been adopted by different OEMs in the world. Outsourcing remanufacturing has been widely adopted in the US and Europe (Karakayali et al., 2007). For example, Land Rover appointed Caterpillar as its lead global remanufacturing services provider (The Auto Channel, 2005). In contrast, in some developing countries, many OEMs prefer to use authorization remanufacturing in recent years (Wang et al., 2014).

Based on the above examples, an OEM has the freedom in choosing remanufacturing partners and remanufacturing modes to maximize its profit. However, at present, it is unclear with regards to the selection of the two remanufacturing modes (i.e. outsourcing and authorization) and two remanufacturers (i.e. CM and IR) that leads to the best outcome for an OEM or the remanufacturing industry.

An OEM’s decision to cooperate with CMs or IRs in its remanufacturing procurement is critical when it intends to use outsourcing or authorization as a marketing tactic. Both CMs and IRs have incentives to seize the remanufacturing opportunities because both are already equipped with the infrastructure and expertise. In the event that the OEM has already outsourced its new products production to the CM. It must consider the CM’s new products production if the OEM chooses to cooperate with the CM again for remanufacturing purpose. By contrast, appointing the IR has no effect on the production of the OEM’s new products which may offer more options for the OEM. In the Apple and Xiaomi case, both have contracted their new products production to Foxconn but they selected different parties for remanufacturing. Apple chose Foxconn again whereas Xiaomi selected an IR. Clearly, whether the remanufacturer participates in the manufacturing process for new products has important ramifications for the OEM’s procurement strategy. Hence, the appointment of a CM or an IR for remanufacturing is a key decision for the OEM.

Our study aims to investigate how should OEMs choose the remanufacturing mode as well as their partners in a supply chain. A game-theoretic model is proposed for this purpose. We consider an OEM that outsources its new products’ production to a CM. The OEM may then choose to cooperate either with a CM or an IR in remanufacturing under two remanufacturing modes (outsourcing and authorization). For conciseness, hereafter we will use *O* to denote the outsourcing remanufacturing strategy and *A* denote the authorization remanufacturing strategy, respectively. For instance, if the OEM chooses to cooperate with a CM in the outsourcing remanufacturing strategy, the procurement structure is called *OM*. A royalty fee has to be paid if the CM or IR wants to engage in remanufacturing for patent protection in the authorization remanufacturing mode.

We investigate these remanufacturing modes from the OEM’s, the CM’s and the IR’s perspectives. Then we attempt to address the following research questions: What is the equilibrium outcome for the OEM under different remanufacturing strategies? What is the optimal response of the CM and IR when they cooperate with the OEM in collection and remanufacturing? How do the remanufacturing strategies affect supply chain members’ profits? And how does remanufacturing influence the decisions of the CM on producing new products?

To provide a full picture of the remanufacturing cooperation process, we divide the analysis in this study into two parts. In the first part, the wholesale price of new products is exogenous, that is, the CM cannot adjust its wholesale price according to the competition between new and remanufactured products. We consider this part for the following reasons. First, in practice, production outsourcing may already exist when a remanufacturing mode or partner is selected, and the wholesale price of new products may have already been decided between the OEM and CM, which can be considered as exogenous. Second, an industry standard price may exist in production outsourcing because intense competition among CMs would result in price alliances or associations among them (Wang et al., 2013). Third, in certain market conditions, the CM may not have enough pricing flexibility to adjust the wholesale price for various reasons (Bolandifar et al., 2016). In the second part, the CM can adjust its wholesale price for new products in response to the OEM’s cooperation strategy. This fits well with situations where the CM has large pricing power or an industry standard price does not exist. The purpose of considering the two parts is to examine the impact of the new production cooperation process on the remanufacturing decisions.

The results of this paper indicate that the OEM has different remanufacturing mode and partner selection in the two settings. When the wholesale price is exogenously given, the authorization mode is more favorable for the OEM. On the contrary, the OEM can gain more profits from the outsourcing mode when the wholesale price is endogenized by the CM. Cooperating with the CM or IR can all be feasible for the OEM under the authorization mode, whereas the OEM should cooperate with the IR in the outsourcing mode. However, the remanufacturer (i.e. the CM or IR) would prefer the outsourcing rather than the authorization mode because the sales quantity of remanufactured products in outsourcing mode is always larger than that of the authorization mode. The authorization mode is also the preferred choice for the CM when it does not engage in remanufacturing as it cannot benefit from remanufacturing. Our findings can provide a better understanding of the firm’s optimal decisions under different settings, which is useful for firms to develop effective operation strategies. Moreover, two remanufacturing modes and potential remanufacturing partners for the OEM are considered in this study.

The rest of this paper is organized as follows. In the following section, we briefly review the previous work. Section 3 presents the description and construction of our models. Section 4 details the optimal responses of the OEM, CM and IR under different remanufacturing strategies when the wholesale price of new products is exogenously given. Section 5 discusses the setting with endogenized wholesale price. Section 6 provides managerial implications of our research. Section 7 concludes the paper and all proofs are provided in the Appendix.

## 2. Literature review

This section reviews four distinguishing features that position our research in the closed-loop supply chain (CLSC) literature: (a) production outsourcing, (b) outsourcing remanufacturing, (c) authorization remanufacturing, and (d) channel selection.

It has been widely believed that outsourcing will continue to gain wide adoption (Stevens, 2009), and the study by Tsay (2014) can serve as an overview of the concept. Many scholars confirm that OEMs can focus on product design and marketing by outsourcing their production processes to external manufacturers (Kakabadse et al., 2005; Chen et al., 2012; Wang et al., 2013; Wang et al., 2014; Bolandifar et al., 2016 and Xu et al., 2018). Chen et al. (2012) investigated whether a large OEM should retain its outsource component procurement. Wang et al. (2013) investigated two parties’ Stacklberg leadership/fellowship decisions when an OEM outsources its manufacturing activity to a CM, whereas the CM can act as both upstream partner and downstream competitor to the OEM. Wang et al. (2014) compared two outsourcing structures (i.e. control and delegation) under both push or pull contract arrangement and found that both the OEM and CM prefer control over delegation under the push contract. However, the OEM prefers control whereas the CM and the supplier prefer delegation under the pull contract. Bolandifar et al. (2016) considered two outsourcing structures in a three-tier supply chain. They considered the effect of competition on the OEM’s component procurement strategies. Xu et al. (2018) investigated a multinational firm’s procurement strategy, which outsources both manufacturing and component procurement to the CM. Their focus is on tax rules, especially on China’s import-export tax and tariff policies. Fan et al. (2020) studied whether an electric vehicle manufacturer should outsource its battery production to a third party or produce in-house. These studies investigated the relationship between OEMs, CMs and suppliers and how the OEMs can achieve higher profits under different outsourcing structures, considering a pull or push contract arrangement, and if competition exists between OEMs. Previous research mainly focuses on outsourcing decisions concerning manufacturing new products. This study aims to extend existing research by considering outsourcing decisions for the production of remanufactured products as well. In particular, this study aims to investigate whether the OEM should cooperate with the original CM or an IR for remanufacturing.

In reality, many OEMs not only outsource new product production but also their remanufacturing operations to external operators, because not all OEMs have the required expertise to remanufacture used products in a profitable manner (Ferguson et al 2010). Remanufacturing activities have recently been carried out primarily by small, independent, and privately-owned outside service providers (Guide, 2000; Hauser and Lund, 2003; Martin et al., 2010). Several studies on the outcomes and decisions pertaining to remanufactured products outsourcing have been conducted. For instance, Majumder et al. (2001) used a game theoretical model to understand the interaction between an OEM and an IR. Savaskan et al. (2004) found that the retailer can perform better than the OEM in used product collection and remanufacturing. Ferrer et al. (2006) pointed that the OEM may forgo some margin by lowering the price of new products to increase the number of used products available for remanufacturing, if an IR has access to collection. Mitra et al. (2008) demonstrated that OEMs may perform better when they compete with IR than operate as a monopolist under government intervention. Örsdemir et al. (2014) characterized how the OEM competes with the IR in equilibrium by considering the following models: monopoly no-remanufacturing, monopoly remanufacturing, and duopoly remanufacturing. Wu et al. (2016) found that the entry of IRs may lead to higher profits for the OEM when a group of functionality-oriented consumers exist. Wanget al. (2017) investigated a retailer’s remanufacturing strategy decision, that is, whether remanufacturing activity should be performed in-house or outsourced. Shi et al. (2020) considered a firm consisting of two divisions, one responsible for new operations and the other responsible for remanufacturing operations, and investigated how a firm’s organizational structure affected its new and remanufactured products marketing decisions. Some studies also considered outsourcing strategy for manufacturers’ warranty service. For instance, Zhang et al. (2020) examined whether the manufacturer should offer warranty service in house or outsource to agents. This study builds on the existing research by modeling the competition between an OEM and an IR when the former does not have manufacturing and remanufacturing capabilities. In this regard, the competition between the OEM and IR exists when the former does not engage its original manufacturer (i.e. CM) in remanufacturing again.

 The related literature concerning remanufacturing authorization is very limited. Some research works related to the remanufacturing of patented products are about policies (Kaufmann et al. 2002, Shane et al. 2006), and some are conducted in the direction of operations management (Oraiopoulos et al., 2012; Abdulrahman et al., 2015; Zou et al., 2016; Liu et al.; 2018; Ma et al., 2018). For instance, Oraiopoulos et al. (2012) demonstrated that the OEM would dominate the secondary market by pricing out the IR, if the OEM decides to refurbish its own products in conjunction with the licensing fee mechanism, whereas Abdulrahman et al. (2015) suggested the OEMs should improve efficiency by increasing remanufacturing patent license fees. Zou et al. (2016) assumed that a patent license fee is needed for remanufacturers’ remanufacturing products if they choose to cooperate with the OEM in the authorization remanufacturing mode, motivated by the example between Apple and Foxconn. Liu et al. (2018) developed Bertrand competition models between an OEM and a third-party reseller to examine the conditions that the refurbishing authorization strategy is optimal for the OEM. They found that the OEM should choose the authorization strategy when the consumer’s preference for refurbished products relative to new products is not large enough. Zhu et al. (2019) investigated how remanufacturing decisions are affect by different market conditions. Ma et al. (2018) identified the conditions under which the OEM and IR would most likely cooperate with each other in remanufacturing under the licensed and unlicensed remanufacturing operations. Zhouet al. (2020) examined how the competition in the secondary market affected the OEM’s authorization decisions, and identified the condition under which an authorization agreement can be reached between the OEM and IRs. However, the license fee payment may differ. Some OEMs charge a license fee to consumers if they want to use a refurbished model, and this often happened in the software industry; examples include Cisco and Sun. Some OEMs charge a license fee to the remanufacturer if they want to engage in remanufacturing, examples include Apple and Huawei. We also contribute to this literature on relicense fee mechanism. In our study, the OEM in the authorization remanufacturing scenario can also collect a licensing fee on remanufactured products sold by the CM or IR because the proprietary rights to remanufacture used products belong to the OEM. Further, we also analyze licensing fees by comparing two remanufacturing modes: authorization remanufacturing and outsourcing remanufacturing.

Concerning remanufacturing mode selections, perhaps the research done by Zou et al. (2016) is most relevant. They considered the remanufacturing mode selection when the OEM competes with the IR in a supply chain, and tries to examine the most favorable outcome. Consistent with them, we also choose the optimal remanufacturing mode. However, we further consider the special relationship between the OEM and remanufacturer CM, i.e., if the OEM chooses to work with the CM in remanufacturing, the CM not only performs remanufacturing operations but also new products production for the OEM. The remanufacturing mode selection may be completely different when the CM acts as both the manufacturer and remanufacturer for the OEM. In addition, we also choose the optimal remanufacturing partner from the perspective of the OEM. The OEM may either cooperate with the original CM or cooperate with an IR in remanufacturing. However, whoever it chooses to cooperate with, they must consider the manufacturing process which is conducted by the CM. The scenario in our study is a relatively common arrangement in practice (e.g. the relationship between Apple and Foxconn).

Numerous research related to the channel selection is also relevant to our research; Savaskan et al. (2004) can serve as a basis. They compared three different distribution channels and chose the appropriate reverse channel structure for collecting used products. In their subsequent research, Savaskan et al. (2006) chose an optimal reverse channel structure. Much research related to channel selections concerns reverse chain design and the difference between direct and retail channels, for example collection alliance and whom to cooperate with for the OEM when collection activities are conducted by different parties. A more comprehensive review can be found in review articles (Guide et al., 2009; Souza, 2013). Ye et al. (2016) identified the upper bounds of efficiency loss in decentralized reverse supply chains by using a systematical analysis. Ma et al. (2020) then examined the upper bounds of efficiency loss in a closed-loop supply chain. Some of the research has considered how to coordinate profits between different channels or supply chain members. Ma et al. (2016) studied channel profits of different cooperative models in a three-echelon closed-loop supply chain consisting of a single manufacturer, a single retailer and two recyclers and examined how cooperative strategies affect supply chain members’ decision making. Hu et al. (2016) studied coordination problems of a decentralized reverse supply chain and proposed five contracts to increase firms’ profits. Ma et al. (2019) examined two financing systems and determined how recycling alliances can affect firms’ channel selection decisions. Some of the research only select the optimal channel for firms. For instance, Zou et al. (2016) compared channel profits of the outsourcing remanufacturing and authorization remanufacturing modes, and chose the optimal channel for the OEM and third-party remanufacturer. Consistent with this stream of literature, the current study also compares the channel profits of different remanufacturing modes and different remanufacturing partner selection strategies.

## 3. Model Assumptions and Notations

We consider a supply chain consisting of a CM, an IR, and an OEM. The OEM uses the CM to manufacture all new products sold by the OEM in the market. However, the OEM has two remanufacturing modes to remanufacture its used products and can work with two remanufacturing partners. The OEM can either choose its original CM or a new IR as its remanufacturing partner by using authorization remanufacturing mode or outsourcing remanufacturing mode. Such a supply chain structure is quite common in the industry. For example, the OEM may be viewed as Apple, Huawei or Xiaomi, while the CM and IR can refer to Foxconn and Aihuishou, respectively.

We are interested in the OEM’s remanufacturing partner strategies and remanufacturing mode strategies in such a model setting. Specifically, a vital question exists for the OEM is: which remanufacturing mode (i.e., outsourcing or authorization) and engagement mode (i.e., CM or IR) are most favorable for the OEM? In order to address this question, we consider a three-stage game among the three players: the OEM, CM and IR. In the first stage, the OEM chooses its remanufacturing mode. The OEM selects its remanufacturing partner in the second stage. After the OEM’s remanufacturing and engagement modes have been decided, the three players set their prices and production quantity in the third stage of the game. The detailed sequence of the events in the second stage will be discussed in the following two sections. Figure 1 depicts four remanufacturing channel models.

In the authorization remanufacturing mode, many ways can be used to share the remanufacturing profit between the OEM and remanufacturer. Similar to Liu et al. (2018), in this paper, we also assume that the OEM uses the piece-rate payment policy in authorization remanufacturing. That is, the OEM charges a licensing fee to the remanufacturer who refabricates used products and retails remanufactured products. The establishment of a licensing fee has been widely used by OEMs as a means of protecting their intellectual property rights and weakens competition from the remanufacturers. From the standpoint of the innovator and the society, royalty licensing is better than an auction if there is a sufficiently large number of potential licensees in the licensing market (Bagchi et al., 2014). In this paper, we assume that the OEM always charges  to the remanufacturer for the sale of remanufactured products. Table 1 summarizes the notations used in this paper.

A consumer will buy a product if and only if his net utility is positive (Chiang et al., 2003). To capture market heterogeneity, we let  represents consumers’ valuation for new products, and their willingness to pay for the remanufactured product as a fraction of a new product.  follows a uniform distribution in the interval . The assumption for lower consumer valuation of remanufactured products is commonly based on existing empirical evidence (Guide and Li, 2010; Subramanian et al., 2012; and Zhou et al., 2013) and applied literature (Hauser and Lund, 2003; Kandra, 2002; Jin et al., 2017 and Zhang et al., 2018). We also assume that the market size is normalized to 1.



**Fig.1.** Four remanufacturing channel models.

A consumer has the net utility  for the new product and  for the remanufactured product. If , then the consumer will prefer the new products over the remanufactured one. Thus, the demand for new products can be given as

  (1)

If , the consumer will buy the remanufactured product. Thus, the demand for remanufactured products can be given as

  (2)

where  and  denote the prices of the new product and remanufactured product respectively. The inverse demand functions can be obtained as follows:

  (3)

  (4)

The demand function is commonly used in the CLSC literature (refer to Souza (2013) for detailed discussions). Note that the demand for new and remanufactured products should subject to , which means that the sales quantity of remanufactured products is lesser than the number of units that can be collected from the consumers. To focus on our main problem, in this paper, we only consider the scenario when . This consideration is quite common in the operations literature, such as Oraiopoulos et al., (2012), Liu et al., (2018) and Zhou et al., (2020). Although new products and remanufactured products can coexist in several periods and be introduced repeatedly, we do not consider multi-period setting and all decisions are considered in a single-period setting. This analysis focuses on the average supply chain profits per period when similar products are introduced to the market repeatedly (Savaskan et al., 2004).

The green remanufacturing program saves the company 40%--65% in manufacturing costs through the reuse of parts and materials (Ginsburg, 2001). As some parts and components can be reused, avoiding the need to produce them from suppliers, the cost of remanufacturing is almost always lower than that of new product manufacturing (Savaskan et al., 2004), i.e., . The cost of collecting used product convexly increases with the collected quantity. We borrow the collection cost function  from the literature (e.g., Zou et,al., 2016; Atasu and Souza, 2013; Jacobs and Subramanian, 2012; Savaskan et al., 2004), where  is the scaling parameter.

**Table 1** Notations.

|  |  |
| --- | --- |
| Symbol | Definition |
| (Model parameters) |
|  | The consumer WTP for the new product |
|  | The consumer value discount for the remanufactured product |
|  | The utility from purchasing a new product |
|  | The utility from purchasing a remanufactured product |
|  | The scaling parameter of the collection cost |
|  | The unit production cost of a new product |
|  | The unit production cost of a remanufactured product |
|  | The unit sale price of a new product |
|  | The unit sale price of a remanufactured product |
| (Decision Variables) |
|  | Total demand for new products |
|  | Total demand for remanufactured products |
|  | The unit wholesale price of a new product |
|  | The unit royalty fee paid by the remanufacturer to the OEM for the sale of remanufactured products |
|  | The unit outsourcing fee paid by the OEM to the remanufacturer for the production of remanufactured products |
| (Others)  |
|  | The profit earned by player *i* in mode *j* and setting *h* |
| Superscript refers to mode *AM, AR, OM*, and *OR,* respectively Superscript refers basic setting and main setting*,* respectively |
| Subscript  refers to the OEM, CM, and IR, respectively |

We separate the analysis into two settings. In the first setting, the CM’s wholesale price for new products is exogenously given which represents the situations where the CM has little pricing flexibility. We call this setting as the basic model and use B in superscript to denote this case. In the second setting, the CM can adjust its wholesale price of the new products according to the competition between new and remanufactured products. We call this setting as the main model and use M in the superscript to denote this case. We next present the CLSC models with remanufacturing operations in authorization and outsourcing modes with respect to the two settings.

## 4. Basic Model—Exogenous Wholesale Price

This section discusses setting exogenous wholesale price, and investigating the three parties’ optimal response in the four remanufacturing models—*AM, AR, OM,* and *OR*. We first discuss the authorization mode (i.e. *AM* and *AR*) in section 4.1, then analyze the outsourcing mode (i.e. *OM* and *OR*) in section 4.2, and finally compare the three parties’ optimal results of the four modes in section 4.3.

### 4.1. Authorization Modes — *AM* and *AR*

In the authorization scenario, the OEM licenses remanufacturing operations to the remanufacturer, i.e. the original CM or IR. The OEM charges a licensing fee to the remanufacturer who refabricates used products and retails remanufactured products, and performs the marketing of the remanufactured products.

In the mode AM, the OEM licenses the remanufacturing operations to the original CM. The CM manufactures new products and remanufactured products. The OEM retails new products in the market, while the remanufactured products are retailed by the CM.

Respectively, the objectives of the OEM and the CM in the mode *AM* are shown as follows:

 (4)

In the mode *AR*, the OEM cooperates with the IR in remanufacturing by using the authorization remanufacturing mode. The CM still manufactures new products for the OEM, but the production and marketing of the remanufactured products are performed by the IR.

Accordingly, the objectives of the OEM, CM, and IR in the mode *AR* are shown as follows:

 (5)

 Since the CM’s wholesale price of the new products is exogenously given, for any given remanufacturing mode and partner selected in the first two stages, the sequence of the game in the third stage is as follows: First, the OEM determines the remanufacturing patent license fee; and then the OEM and remanufacturer decide their sales quantity of new products () and remanufactured products () simultaneously and non-cooperatively. The sequence of the game in the third stage is similar to that of Wang et al. (2013).

It can be proved that the Hessian matrixes of profit functions are negative definite, which implies the concavity of profit functions. The optimal decisions of three firms are derived in Proposition 1.

**Proposition 1.** In the authorization remanufacturing mode when the wholesale price of new products is exogenously given, the optimal responses are the same for the three parties in the *AM* and *AR* modes. The equilibrium authorization fee, sales quantity and profits are:

1. , , ;
2. , , , .

In the equilibrium market structure, the sales quantity of new and remanufactured products need to be nonnegative and satisfy certain conditions (i.e.,  and ). We characterize the equilibrium with two thresholds in . Therefore, the coexistence of new and remanufactured products arises only when . This condition is the feasible condition for Proposition 1, and all the following analysis and comparison relate to modes *AM* and *AR* are strictly restricted to this condition.

Proposition 1 reveals an important implication, that is, regardless of who to cooperate with, the OEM earns equal profits in the authorization remanufacturing mode when the wholesale price of new products is exogenously given. This indicates that the remanufacturing partner selection has no effect on the OEM’s optimal authorization fee and sales quantity of new products, and the remanufacturer’s sales quantity of remanufactured products. The reason is that the OEM and the remanufacturer always face the same optimal problems when the wholesale price of new products is exogenously given. However, the CM is always worse off for losing remanufacturing business.

Proposition 1 also provides several conclusions about the wholesale price’s impact on the equilibrium outcome. A higher CM’s wholesale price for new products always results in a lower authorization fee, a smaller sales quantity of new products, but a higher sales quantity of remanufactured products. However, the wholesale price’s overall impact on the OEM’s and CM’s profit depends on its influence on the sales quantity of new and remanufactured products. A high wholesale price can benefit or hurt the OEM and CM, as it increases the sales quantity of remanufactured products and decreases the sales quantity of new products. The IR can always benefit from a higher wholesale price of new products because it not only increases the demand for remanufactured products but may also decrease the CM’s profit.

### 4.2. Outsourcing Modes — *OM* and *OR*

In the outsourcing remanufacturing scenario, the OEM can outsource the remanufacturing operations to the original CM or IR. At the same time, the OEM pays the remanufacturer an outsourcing fee. Hence, the OEM retains the marketing operations of new products and remanufactured products.

In the mode *OM*, the OEM outsources the remanufacturing operations to the original CM. The CM only manufactures new and remanufactured products. The marketing of new products and remanufactured products is to be performed by the OEM.

Respectively, the objectives of the OEM and CM in the model *OM* are shown as follows:

 (6)

In the mode *OR*, the OEM outsources the remanufacturing operations to the IR. The CM manufactures new products for the OEM whereas the IR produces remanufactured products.

The objectives of the OEM, CM, and IR in the mode *OR* are shown as follows:

 (7)

In the first stage, the OEM selects its remanufacturing mode, and then chooses its remanufacturing partner in the second stage. Finally in the third stage, the game of the sequence is as follows: the remanufacturer (i.e. IR or CM) first determines the outsourcing fee (), and then the OEM and remanufacturer decide their sales quantity of new products () and remanufactured products () simultaneously and non-cooperatively.

Similarly, it can also be proved that the Hessian matrixes of profit functions are negative definite. The optimal decisions of the three firms are derived in Proposition 2.

**Proposition 2.** In the mode *OM*, the equilibrium outsourcing fee, sales quantity and profits are:

1. , , ;
2. , .

In the mode *OR*, the equilibrium outsourcing fee, sales quantity and profits are:

1. , , ;
2. , , .

Similarly, the feasible conditions for the mode OM are: . And the feasible conditions for the mode OR are: .

Proposition 2 provides several conclusions concerning the impact of wholesale price on new products. A higher wholesale price of new products always results in a higher outsourcing fee, larger sales quantity of remanufactured products and lower sales quantity of new products in the two outsourcing modes. However, in the mode *OM*, the sales quantity of remanufactured products is invariant to the wholesale price. The IR can always benefit from a higher wholesale price of new products. However, a higher wholesale price may not always benefit the OEM and CM though it allows the remanufacturer to charge a higher outsourcing fee and the CM to sell more remanufactured products.

In contrast with the previous section in which the remanufacturing partner selection does not affect the OEM’s and remanufacturer’ optimal response and profits, we find that the three parties equilibrium outcomes are different in the two outsourcing modes. We compare the two outsourcing modes in the following corollary.

**Corollary1.** The optimal outsourcing fee and sales quantity in the two outsourcing modes when the wholesale price is exogenously given are related as follows: ,  and . The OEM’s profits in the two outsourcing modes are related as follows: .

Corollary 1 shows that the OEM can always obtain a higher profit by cooperating with the IR than its original CM. From comparing the equilibrium outcomes, we know that the remanufacturer would always charge a higher outsourcing fee for remanufactured products in the mode *OM* which leads to a lower sales quantity of remanufactured products. The OEM can earn higher profits from selling remanufactured products in the mode *OR* than *OM* though the existence of remanufactured products can cannibalize consumers’ demands for new products. The OEM’s profit loss in selling new products can be offset by selling remanufactured products in the mode *OR*.

### 4.3. Authorization vs. Outsourcing

From section 4.1 and section 4.2, we know that the remanufacturing partner does not affect the OEM’s profit in the authorization mode whereas the OEM can always earn higher profits by cooperating with the IR in the outsourcing mode. However, it remains unknown as to which remanufacturing mode the OEM should choose and the modes’ impact on the CM’s and IR’s profits. Hence, we compare the four remanufacturing modes in the following.

**Proposition 3.** Comparing the four remanufacturing modes when the wholesale price is exogenously given shows that the three parties’ profits are related as follows:

1. The OEM’s profits are ;
2. When the CM acts as the remanufacturer, the CM’s profits are ; the CM’s profits are related as  when the CM does not engage in remanufacturing;
3. The IR’s profits are .

The results in Proposition 3 show that the OEM is always better off in the authorization mode and this strategy can be the dominant strategy for the OEM. In this scenario, cooperating either with the original CM or the IR does not affect the OEM’s profits. The CM also prefers to cooperate with the OEM in the authorization mode when it does not engage in remanufacturing. However, when the CM engages in remanufacturing or the IR acts as the remanufacturer, they would always prefer to cooperate with the OEM via the outsourcing remanufacturing mode. The main difference between the two remanufacturing modes is whether the OEM interferes with the remanufacturing market directly or not. In the authorization mode, the OEM does not interfere with the remanufacturing directly while the OEM directly interferes with the market by selling remanufactured products in the outsourcing mode. The OEM can sell more new products (i.e. ) and less remanufactured products (i.e.  ) to consumers in the authorization mode than the outsourcing mode which indicates that the OEM earns higher profits from new products in the authorization mode. Consequently, the OEM’s profits in the authorization mode is higher than that of in the outsourcing mode. This also explains why the remanufacturer CM or IR prefers the outsourcing mode than authorization mode because it can sell more remanufactured products in the outsourcing mode which is a main profit for a remanufacturer. When the CM does not engage in remanufacturing, it also prefers the authorization mode as the OEM does.

## 5. Main Model—Endogenized Wholesale Price

In contrast with the previous section, in which the CM cannot adjust its wholesale price, this section considers the setting in which the wholesale price is endogenized by the CM. This consideration can be found in other operations management and marketing research studies, such as those of Wanget al*.* (2013). In the endogenized wholesale price setting, the objectives of the OEM, CM and IR are the same as that of in the exogenous wholesale price setting except that the CM can adjust its wholesale price according to the competition between the new and remanufactured products, and the OEM’s remanufacturing mode and engagement strategy.

### 5.1. Authorization Modes — *AM* and *AR*

Since the wholesale price is endogenized by the CM, the game in the first two stages are the same while the sequence of the events in the third stage is revised as follows: the CM first determines the wholesale price of new products (); and then the OEM sets the unit authorization fee () for remanufactured products; and finally the OEM and the remanufacturer determine their sales quantity of new products () and remanufactured products () simultaneously and non-cooperatively.

The problem can be solved by backward induction. The sequence of the events in the third stage is the same as that of in the basic model except that the CM must decide the wholesale price first. The optimal wholesale price can be obtained by substituting the results in Proposition 1 into the CM’s profits functions. To avoid repetitiveness, we only list the optimal wholesale price in the following. The equilibrium outcomes can be obtained accordingly.

**Proposition 4**. In the mode *AM*, the optimal wholesale price is . In the mode *AR*, the optimal wholesale price is .

The CM would set different wholesale price in the mode *AM* and mode *AR* which consequently leads to different equilibrium outcomes for the three parties though the three parties have the same equilibrium responses when the CM cannot adjust its wholesale price. The CM would increase its wholesale price when it has high production cost of new products () in the two modes. However, the wholesale price increases with the production cost of remanufactured products () in the mode *AM*  but decreases with  in the mode *AR*. A higher production cost leads to a lower profit for the CM when it engages in remanufacturing and hence, the CM would increase the wholesale price to offset its profit loss. While in the mode *AR*, the CM does not engage in remanufacturing. The remanufactured products would become more competitive in the market when the IR has a low production cost or consumers have high valuation for the remanufactured products. The CM has to decrease the wholesale price to increase the attractiveness of new products. Besides, we also notice that , that is, the wholesale price in the mode *AM* is always larger than that of in the mode *AR*. The CM can benefit from the remanufacturing business in the mode *AM*, then it can charge a higher wholesale price for the new products. While in the mode *AR*, the CM has to decrease the wholesale price of new products to increase the sales quantity and its profits.

The feasible conditions for modes AM and AR are obtained by respectively substituting the optimal  and  into . In the following, we compare the two authorization modes to select the remanufacturing partner for the OEM.

**Corollary 2.** The optimal authorization fee and sales quantity in the authorization modes when the wholesale price is determined by the CM are related as follows: ,  and . The OEM’s profits in the two authorization modes are related as follows:  under the condition , while  under the condition , where .

Corollary 2 shows that the OEM would always charge a higher authorization fee in the mode *AR* than *AM*, and the higher authorization fee leads to a lower sales quantity of remanufactured products. However, in the mode *AR*, the OEM can sell more new products to consumers. These results are completely different from the case when the wholesale price of new products is exogenously given in which the selection of the remanufacturing partner does not affect the OEM’s profit. However, when the CM has the pricing flexibility and can adjust the wholesale price accordingly, the selection of the remanufacturing partner would affect the OEM’s profit. As shown in Proposition 4, the CM would set a higher wholesale price in the mode *AM* than *AR*. This causes the OEM to increase its sales price for new products and consequently, decreases its sales quantity. However, the higher authorization fee and larger sales quantity of new products do not necessarily lead to a higher profit for the OEM in the mode *AR*. Only when the production cost of remanufactured products is small enough, the OEM should cooperate with the IR in the authorization remanufacturing mode. Otherwise, the OEM should sign an agreement with its original CM again in remanufacturing. This is because the sales quantity of remanufactured products in the mode *AM* is larger than that in the mode *AR*. The OEM can still gain more profits from authorization though it would charge a lower authorization fee. The competition between new and remanufactured products causes the CM to sell less new products but more remanufactured products. Such decrease or increase can either hurt or benefit the OEM.

### 5.2. Outsourcing Modes — *OM* and *OR*

In the outsourcing modes when the wholesale price is endogenously determined by the CM, the sequence of the events in the third stage is revised as follows: the CM first determines the wholesale price of new products (); then the remanufacturer sets the outsourcing fee () for the remanufactured products; and finally the OEM and the remanufacturer determine their sales quantity of new products () and remanufactured products () simultaneously.

For brevity, we only list the optimal wholesale price. The equilibrium outcomes can be obtained by substituting the optimal wholesale price into Proposition 2.

**Proposition 5**. In the mode *OM*, the optimal wholesale price is . In the mode *OR*, the optimal wholesale price is .

Proposition 5 shows that the CM’s wholesale price is only affected by the production cost of new products in the mode *OM* and increases with . While in the mode *OR*, the CM’s wholesale price is not only affected by the production cost of new products (), but also affected by the production cost of remanufactured products (), consumers’ valuation (), and the scaling parameter (). In the mode *OR*, the CM would decrease its wholesale price of new products when the remanufacturing business is highly profitable (i.e.  and  are small, is large). The new products can become more attractive to consumers when the CM decreases the wholesale price. This makes consumers more likely to purchase a new product. In addition, the CM would always set a lower wholesale price in the mode *OR* than in the mode *OM*, as . The remanufacturing business is conducted by the IR in the mode *OR*. Therefore, the CM has to decrease its wholesale price to increase the order quantity from the OEM and consumers’ demands for new products.

According to the optimal wholesale price on modes OM and OR, the feasible conditions in mode OM are modified to . And the feasible conditions in mode OR are modified to .

**Corollary 3.** The optimal outsourcing fee and sales quantity in the outsourcing modes when the wholesale price is determined by the CM are related as follows: ,  and . The OEM’s profits in the two outsourcing modes are related as .

Consistent with the previous section in which the wholesale price is exogenously given, the OEM is always better off by cooperating with the IR rather than the CM. However, in this setting when the wholesale price is endogenously determined by the CM, the OEM is better off in the mode *OR* because the OEM can always sell more new and remanufactured products to consumers. A high wholesale price and outsourcing fee induce the OEM to decrease its sales quantity of new and remanufactured products, which consequently, decreases the OEM’s overall profits in the mode *OM*. Cooperating with the CM again in remanufacturing becomes less attractive when the CM charges a higher wholesale price of new products as new and remanufactured products coexist in the same market.

### 5.3. Authorization vs. Outsourcing

From section 5.1 and section 5.2, we know that, in the authorization remanufacturing mode, the OEM’s remanufacturing partner selection highly depends on the production cost whereas the OEM should always cooperate with the IR using outsourcing mode. However, which remanufacturing mode is better for the OEM, the CM and the IR remains unanswered. In this section, we compare the four remanufacturing modes to select the optimal mode for the three parties.

**Proposition 6.** Comparing the four remanufacturing modes when the wholesale price is endogenized shows that the three parties’ profits are related as follows:

1. The OEM’s profits are related as ;
2. When the CM acts as the remanufacturer, its profits are related as ; when the CM does not act as remanufacturer, the CM’s profits are related as  under the condition and  under the condition , where ;
3. The IR’s profits are related as .

Proposition 6 provides several conclusions about the optimal remanufacturing mode and partner engagement strategy for the OEM, the CM and the IR. Compared with the wholesale price when it is exogenously given, we find that some results still hold. For instance, the remanufacturer is always better off in the outsourcing mode than in the authorization mode, i.e.  and . As we have explained earlier, the remanufacturer can always sell more remanufactured products to consumers in the outsourcing mode than in the authorization mode. This increases the remanufacturer’s profits. However, several distinctions exist between the two settings. It would be better for the OEM to cooperate with the IR in the outsourcing mode when the CM can adjust its wholesale price. The remanufacturing partner selection can affect the OEM’s optimal profits. In the mode *OR*, the CM would always set the wholesale price at the lowest to induce the OEM to expand the market share of new products as the CM cannot benefit from remanufacturing. The low wholesale price causes the IR to decrease its outsourcing fee. The OEM can benefit from the low wholesale price and outsourcing fee as the low price can increase the sales quantity of new and remanufactured products. Besides, we also notice that the CM’s profits in the mode *AR* is not always larger than that of in the mode *OR*. Only when the remanufacturing business is profitable enough, the CM prefers the authorization mode. This is because, when the CM does not engage in remanufacturing, it can decrease the wholesale price to increase the attractiveness of new products in the mode *OR*. The CM can gain more profits in the mode *OR* than that of in the mode *AR* when the production cost of remanufactured products is high.

## 6. Managerial Implications

In this section, we discuss several implications from the analysis we conducted. First, the selection of remanufacturing modes (i.e. outsourcing and authorization) and remanufacturers (i.e. CM and IR) depends on specific conditions. For the OEM, when the wholesale price is exogenously given, both remanufacturers (i.e. CM and IR) are optimal choices in the authorization mode. However, when the CM has pricing flexibility and can adjust its wholesale price, the OEM should cooperate with the IR using the outsourcing mode. Therefore, the OEM’s decision to choose its remanufacturing mode and engagement strategy is influenced by its ability to adjust the wholesale price. The remanufacturer can always sell more remanufactured products in the outsourcing mode. Therefore, for the IR and the CM, when they engage in remanufacturing, the outsourcing mode is more favorable than the authorization mode. However, when the CM does not engage in remanufacturing, authorizing can be more profitable than outsourcing.

Our results can serve as a guidance for the OEM who seeks a remanufacturing partner in the market. For instance, Apple engaged Foxconn as its official remanufacturer via the authorization mode whereas Huawei and Xiaomi signed an agreement with an IR—Aihuishou, while appointed Foxconn as their CM. In the Apple’s and Foxconn’s case, Foxconn usually does not have pricing flexibility, and this can be considered as the wholesale price in the exogenously given setting. Our model shows that remanufacturing partner selection does not affect the OEM’s optimal decisions when the wholesale price is exogenously given. Therefore, cooperating with Foxconn or a third party can both be equivalently optimal for the OEM (i.e. Apple). This explains why the Apple added Phobio, a third party, as its remanufacturing partner in the European market (Phobio, 2017). While in the Huawei’s and Xiaomi’s case, the scenario is completely different. The CM may adjust its wholesale price accordingly which leads to a completely different strategy for these parties. However, we acknowledge that many factors would affect the OEM’s remanufacturing partner and mode selections. The wholesale price is just a factor that affects the OEM’s optimal decisions.

## 7. Conclusion

In order to focus on core competencies such as product design and marketing, many OEMs choose to outsource its production to the CMs. OEMs are compelled to pay more attention to remanufacturing because of the shortage of natural resources and government interventions. However, many OEMs do not have the ability to manage their remanufacturing activity in a profitable manner. They have to work with the original CMs or the IRs in remanufacturing operations. Two options exist for the OEMs when it comes to remanufacturing, viz, outsourcing remanufacturing and authorization remanufacturing. Both remanufacturing modes are used by different OEMs in practice. Motivated by the cases of Apple and Foxconn, Xiaomi and Aihuishou, we try to choose the optimal remanufacturing mode as well as the best remanufacturing partner for the OEM, and also choose the most profitable arrangement for the CM and IR. We conducted the research to answer questions such as which mode the OEMs would prefer, who the OEMs should work with, which mode the CM and IR would prefer, and how remanufacturing would influence the decisions of the CM on producing new products. By analyzing the players’ equilibrium optimal solutions in the authorization and outsourcing remanufacturing scenarios respectively, some interesting findings are obtained.

First, the optimal strategies of the OEM, CM and IR are influenced by multiple parameters, including the production cost of new and remanufactured products, collection cost and consumers’ valuation of remanufactured products. The influences of these parameters vary in different models, and we only focus on analyzing the influence of the costs of new products and remanufactured products.

Second, our comparisons of the four remanufacturing modes when the wholesale price is exogenously given suggest that the OEM always prefers the authorization mode than the outsourcing mode, whereas for the remanufacturer (i.e. either the CM or IR), it would always prefer the outsourcing mode. In the authorization mode, the remanufacturing partner selection does not affect the OEM’s optimal response and the OEM can obtain equal profits whether it cooperates with the original CM or IR. This implies that modes *AM* and *AR* can be optimal for the OEM when the CM does not have pricing flexibility and cannot adjust its wholesale price. When the CM does not engage in remanufacturing, it would prefer the authorization mode than the outsourcing mode. However, the authorization mode would lead to a lower profit for the remanufacturer as the sales quantity of remanufactured products may decrease correspondingly.

Third, our comparisons of the four remanufacturing modes when the wholesale price is endogenously determined by the CM suggest that some of our results obtained in the exogenous wholesale price setting still hold but some are completely different. For the remanufacturer, whether the IR or the CM engages in remanufacturing, it always prefers the outsourcing mode over the authorization mode. However, for the OEM, cooperating with an IR in the outsourcing mode is the optimal strategy rather than the authorization mode. In the mode *OR*, the OEM can not only sell more remanufactured products but more new products to consumers as the CM would always set a lower wholesale price in this scenario.

Some of our results are consistent with Zou et al. (2016), but a number are surprising. They concluded that the OEM prefers the outsourcing mode than the authorization mode, and the mode that the third-party remanufacturer prefers depends on the acceptance of remanufactured products. However, they did not consider the scenario when the OEM does not have the manufacturing capability and when the original CM can act as the remanufacturer again. Our results also confirm that, in the endogenous wholesale price setting, the outsourcing mode is the favorable choice for the OEM. In this setting, cooperating with the IR (i.e. mode *OR*) is the dominant strategy for the OEM. However, when the wholesale price is exogenously given, the authorization mode can be more beneficial for the OEM. Further, cooperating with the CM or IR is all feasible as the partner choice does not affect the OEM’s optimal response. Besides, we also show that, for the remanufacturer, the outsourcing mode is more favorable than the authorization mode. Our results can tangibly assist firms in choosing the appropriate remanufacturing mode as well as partners when there is a special relationship between the OEM and CM, i.e., the CM can act not only as a manufacturer, but as a remanufacturer.

In this paper, we offer new insights for the OEM who faces remanufacturing mode options and does not know who to work with in remanufacturing when it has already outsourced its production to the CM. We also offer insights to the original CM who manufactures new products and might also produce remanufactured products for the OEM, and to the IR who specializes in remanufacturing and wishes to earn profits from remanufacturing used products. The results can be helpful to firms’ pricing decisions, and assist firms in choosing the appropriate remanufacturing mode and partner. However, the quality of used products is not considered in this study. In fact, the quality variety of used products may affect remanufacturing, and this can further affect the remanufacturing mode and partner selection, which deserves further research.

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## Appendix: Proofs

**Proof of model *AM* when the wholesale price is exogenous given**

The problem can be solved by backward induction. We first solve the OEM’s and CM’s optimal problem with respect to and , and then substituting these results back to get the optimal authorization fee . The decision problems faced by the OEM and CM are given by  and . Because of the second-order sufficient condition, i.e., , ,  is strictly concave in , and  is strictly concave in . As the OEM and the CM make decisions independently and simultaneously, we can derive optimal decisions by solving the first-order conditions.

The first-order derivatives of  with respect to  and  with respect to are  and . Letting  and solving simultaneously, we obtain  and .

Then, substituting into . The first-order derivatives of with respect to  are . Because of the second-order sufficient condition, i.e.,  is negative, the profit function is concave in. Letting, we obtain .

Then, substituting into and profits functions of the OEM and the CM, the equilibrium outcomes in Proposition 1 can be obtained.

Here we only give the proof process of the mode *AM* when the wholesale price is exogenously given. The proof of the modes *AR*, *OM* and *OR* when wholesale price is exogenously given and when wholesale price is endogenized is similar to that of the proof in the mode *AM*, so we omit the proof process.

**Proof of Corollary 1**

To solve the difference of the quantities and profits in the mode *OM* and mode *OR* when the wholesale price is exogenously given, we have









Based on the difference, it is easy to prove Corollary 1.

**Proof of Proposition 3**

To prove Proposition 3, we need to compare the OEM’s, the CM’s and the IR’s profits in the four remanufacturing modes when the wholesale price is exogenously given. We first compare the OEM’s profits in the four remanufacturing modes. As we already know  and , we only need to compare ,  with  or . Then, we have . Based on the OEM’s profits difference in the modes *AR* and *OR*, it is easy to prove the OEM’s profits relationship in the four modes.

We then compare the CM’s profits in the four remanufacturing modes. When the CM acts as the remanufacturer, the profit difference is



When the CM does not act as the remanufacturer, the profit difference is



We finally compare the IR’s profits when the OEM cooperates with the IR in remanufacturing, we have .

Based on these, it is easy to prove Proposition 3.

**Proof of Corollary 2**

To solve the difference of quantities and profits in modes *AM* and *AR* when the wholesale price is endogenously determined by the CM, we have









It is easy to prove ,  and  as . However, to prove the relationship between  and , we need to solve the roots of . To solve the roots of , we have  or Because the second root is smaller than 0, and hence we do not consider it. Therefore,  when , and  under the condition .

**Proof of Corollary 3**

To solve the differences of quantities and profits in modes *OM* and *OR* when the wholesale price is endogenously determined by the CM, we have



It is easy to prove ,  and . However, it is not easy to prove the OEM’s profits. Hence, we have

It is easy to prove  as .

**Proof of Proposition 6**

To prove Proposition 6, we need to compare the OEM’s, the CM’s and the IR’s profits in the four remanufacturing modes when the wholesale price is endogenously determined by the CM. From Corollaries 2 and 3, we know that ,  under the condition , and  under the condition . Therefore, if we want to know the difference of the equilibrium profits of the OEM in the four models, we only need to solve the difference of the profits in modes *AM*, *AR* and *OR*. To solve the difference of the profits in modes *AM* and *OR*, *AR* and *OR*, we have





It is easy to prove ,  as . Therefore, the OEM’s profits in the four modes are always satisfied .

When the CM acts as the remanufacturer, the CM’s profits difference in modes AM and OM is

When the CM does not act as the remanufacturer, the CM’s profit difference in modes *AR* and *OR* is

To solve the roots of , we have . As , hence , .

To solve the IR’s profit difference in modes *AR* and *OR*, we have

Q.E.D.

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