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MODULAR DESIGN OF NEW PRODUCTS AND REMANUFACTURING OF USED PRODUCTS UNDER MASS CUSTOMIZATION

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Abstract. Modular architecture design can not only increase the product variety and thus make mass customization (MC) easier, but also improve interchangeability and then lower the remanufacturing cost. This paper models a remanufacturing MC supply chain with one manufacturer and one retailer. The manufacturer, as a Stackelberg game leader, designs and then sells the new and modular MC products *via* its brand retailer, and meanwhile the remanufacturing of used MC products would be carried out by either the manufacturer or the retailer. We study the optimal modular design for new MC products and the best remanufacturing mode for used MC products. One centralized and two decentralized decision models are formulated, and the equilibrium solutions of proposed models are compared and analyzed. Findings show that, compared to the retailer-remanufacturing mode, the manufacturer-remanufacturing mode can be superior in terms of the ability to cope with customer customization requirements (*i.e.*, the modularity level), total supply chain profit, and consumer surplus. Moreover, both supply chain members and consumers would prefer the manufacturer-remanufacturing mode when the parameters meet certain conditions. We also extend the model to two scenarios: the remanufacturing is bounded by cores supply and the retailer acts a leader, so as to verify the robustness of main results. The above theoretical results are verified by numerical examples.

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1. Introduction

1.1. Background and motivation

Modularity designs one integrated product into many relatively independent modules, which can be combined in different ways to form a variety of final products. This enables mass customization (MC) firms to quickly cope with customer's customized requirements at a cost close to mass production. For example, Dell allows customers to assemble computers through modular options on its online store and then delivers the customized computers based on customer's specific requirements [38]. By designing customizable color and material modules for interior design, various automobiles brands, such as BMW and Ford, are also providing MC service for consumers [6]. Moreover, combining the online retailer's advantages in understanding customer needs with Apple's ability of offering customizable color, configuration, and carving modules, Apple sells custom computers through JD

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and personalized Apple Watch Band through Amazon in addition to offering MC service on its own website [41]. On the other hand, product modularity can also increase the ease of recycle and reuse when it comes to remanufacturing disposal, thereby making it more cost-effective to remanufacture the modular products compared to the integrated products [19, 40]. For instance, a case study of Xerox photocopier suggests that remanufacturing modular copiers can save 49% in materials and 68% in energy consumption, whereas these two savings are only 25% and 27% if the non-modular ones are remanufactured [17], which enables Xerox Corporation to earn nearly $200 million from remanufacturing [8]. As a result, modular architecture design can not only increase the product variety and thus make MC occur easier [26,41], but also improve interchangeability and then reduce the remanufacturing cost [4,46], which makes it possible to combine customization with remanufacturing *via* modularity.

In practice, manufacturers are willing to operate the remanufacturing business for the sake of improving brand social image or profitability. For example, Dell launches the DellReconnect project with Goodwill to recycle more waste electronics for remanufacturing [14], and also establishes a separate web site to sell its remanufactured computers [29]. Additionally, BMW establishes a remanufacturing gearbox factory for specialize in steering gear [23]. However, some manufacturers are unable or reluctant to operate the remanufacturing business, because they lack the infrastructure and expertise to remanufacture the used products or need to focus the time and resources on new products production. Such as Ford, who once acquired several auto salvages yards and parts recycling firms in order to reap the potential economic benefit from disposing used vehicles, has to abandon the remanufacturing business because of its inexperience in the remanufacturing field [16]. Apple signs the proprietary rights of remanufacturing used iPhone to Foxconn, and redirects its resources to the design and production of new products [54]. In actual operation, the retailers, who have the advantages of proximity to consumer market, can also operate the remanufacturing business. For instance, Oruid Automobile Engine Technology (a retailer in Guangzhou) produces and sells remanufactured engines in addition to reselling the new auto parts provided by BMW [28]. JD and Amazon separately launch Paipai and Amazon Renewed on their own sites, covering collecting, testing, leasing, and transaction of the secondhand products, so as to satisfy consumer demand for the remanufactured products with low price [39, 53].

Based on the aforementioned case observations, to concurrently cope with consumer needs for personalization and low price but environmental protection, MC and remanufacturing can be effectively combined owing to the advantage of modular design. The manufacturer is then pressured to decide whether to remanufacture used MC products itself in addition to producing new MC products. When the manufacturer operates the remanufacturing business of used MC products (*i.e.*, manufacturer-remanufacturing mode), it can earn an extra income from the second market and also retain the pricing right for remanufactured MC products *via* wholesale price, whereas it needs to bear the remanufacturing cost that can be reduced by modular design. If the manufacturer is reluctant to remanufacture used MC products, the retailer operates the remanufacturing business (*i.e.*, retailer-remanufacturing mode). In this case, even if the free-riding retailer can benefit the remanufacturing cost savings related to product modularity and without bearing the modular design cost, it might be deterred by the MC manufacturer at the expense of weakening the ability to cope with customer customization needs, *i.e.*, reducing the modular design investment. Consequently, for MC manufacturer and its brand retailer, who ought to remanufacture the used MC products is a dilemma.

It is generally accepted in literature that the modularity level can be taken to characterize the investment results of modular design [9, 24, 27, 41]. The more investment in modular design, the higher modularity level would be obtained. Although a higher modularity level can reduce the remanufacturing cost in reverse logistics, as well as enhance products diversity and then increase demand in forward logistics, modular design is also costly. Hence, after weighing the design cost against remanufacturing cost savings and demand income, the MC manufacturer under manufacturer-remanufacturing mode needs to determine an optimal modularity level. Nevertheless, under retailer-remanufacturing mode, the MC manufacturer faces a dilemma of determining the modularity level: on the one hand, a choice of higher modularity level can increase the product variety and thus make MC implementation easier, while this also saves more remanufacturing cost for the free-riding retailer that bears no modular design costs; on the other hand, decreasing the modularity level to deter the free-riding retailer, would simultaneously weakening the MC manufacturer's ability coping with customer customization needs. Therefore, among different remanufacturing modes, how for MC manufacturer to set the optimal modularity level is an important issue.

A review of existing literature reveals that that there is no research that combines customization service with remanufacturing business *via* product modularity. This paper is clearly distinguished from works on process innovation for remanufacturing [31], since in this paper the modular design not only improves product interchangeability, thereby reducing remanufacturing cost for manufacturers or retailers and creating more circular economy, but also increases product variety, thereby making MC occur easier and generating more orders (while process innovation cannot directly affect demand). Motivated by the dual role of modularity in MC and remanufacturing along with the research gap in literature, this paper is the first to study the optimal modularity level for new MC products and the best remanufacturing mode for used MC products.

1.2. Research questions and contributions

In this paper, we focus on examining the new-product modular design and used-product remanufacturing mode under MC. We consider a remanufacturing MC supply chain consisting of one manufacturer and one retailer, in which the upstream manufacturer designs and then sells the new, modular MC products *via* its downstream brand retailer, while the manufacturer or the retailer also remanufactures the used MC products with modular architecture design. Based on the actor who undertakes the remanufacturing of used MC products, one centralized and two decentralized decision models are constructed: (1) the centralized decision model, called Model C, which is an ideal supply chain system without double marginal effect and acts as a benchmark for the decentralized system; (2) the manufacturer-remanufacturing decision model, called Model M; (3) the retailer-remanufacturing decision model, called Model R. The core research questions (RQs) are as follows.

RQ 1. What is the optimal modularity level for new MC products among different remanufacturing modes?
RQ 2. Which is the best remanufacturing mode for used MC products?
RQ 3. How does the modular design of MC products influence the remanufacturing supply chain?

Note that, third-party remanufacturing is also a classic remanufacturing mode, whereas there are still some problems for this mode. For instance, third-party remanufacturing would cannibalize the market of original manufacturer [16]; the patent rights of original manufacturer might be infringed by the third-party remanufacturer [42]; supply chain often performs worse with a longer decision hierarchy [56]. Hence, following Reimann *et al.* [31] and Zhang and Zhang [51], this paper only considers two decentralized remanufacturing modes, which is conducted by the upstream manufacturer or the downstream retailer.

This study makes the following contributions. First, few literatures investigate the customization and remanufacturing at the same time. According to the advantages of product modularity in coping with consumer individual requirements along with improving interchangeability degree, this paper is the first to combine mass customization operation and remanufacturing management, which can provide evidence for the development of remanufacturing MC supply chain in practice. Second, by using consumer's Hotelling utility theory, this paper theoretically derives the relationship between the modular design and the demand for the new as well as remanufactured MC products, whereas existing research simply assumes that market demand increases linearly in the modularity level without theoretical basis. Third, this paper also reminds MC firms to focus on the impacts of modular design on optimal pricing decisions and consumer surplus under remanufacturing, and then helps firms in a remanufacturing MC supply chain to adjust prices for more marginal revenue without compromising consumer welfare.

The rest structure of this paper is organized as follows. Section 2 reviews the relevant literature. Section 3 shows the model construction. Section 4 compares and analyzes the equilibrium solutions of proposed models. The numerical analysis is presented in Section 5. Two extensions are presented in Section 6 for verifying the robustness of results in base models. Section 7 concludes and discusses this study. The proof is supplemented in Appendix.

2. Literature review

The literature review of this paper is surveyed from two aspects: modularity and mass customization; remanufacturing supply chain management.

2.1. Modularity and mass customization

Modularity is the essence of MC [9, 20], since it can enable product variety [18], enhance manufacturing flexibility [1], and then improve MC capability [52]. The modularity level refers to the degree to which the components of a system can be separated and reorganized [27], which can be taken as a strategy to measure MC level [20]. Due to the role of modularity in MC implementation and return handling, the modularity level is a major decision in the MC supply chain with consumer returns. For example, *via* a mean-variance model, Liu *et al.* [24] investigated the joint decisions of retail price, refund amount, and modularity level for MC products with uncertain demand. Under the competition and cooperation between upstream manufacturers and downstream assemblers, Li *et al.* [22] identified the optimal modularity level, pricing, return policy and lead time of MC products. Guo and Liu [9] derived the optimal modularity level in a capital-constrained MC supply chain, and investigated the impacts of supply chain finance on MC program from the perspectives of cash flow shortage and risk attitudes. Expanding offline MC to online MC, Wang and He [41] examined the optimal modularity level, return policy, and pricing decisions for online MC products in a dual-channel supply chain. The above study simply assumes that demand increases linearly in the modularity level, which lacks the theoretical basis. In essence, modularity can generate higher demand since the modular product is customized with respect to the consumer's requirements and then provides greater utility and satisfaction [40]. Based consumer's Hotelling utility theory, this paper rationally derives the relationship between the modularity level and the market demand for new and remanufactured MC products. The combination of MC operation and supply chain management also generates some other important topics, such as inventory management [11], channel coordination [12], and supply chain integration [37], whereas the research on remanufacturing MC supply chain is limited. Inspired by Guo *et al.* [10] who reviewed that both manufacturer-as-leader and retailer-as-leader are prevailing single-leader situations in reverse logistics, for supply chain models with remanufacturing and MC, this paper first considers the manufacturer-led Stackelberg game and then extends to the retailer-led game for verifying the robustness of main results.

2.2. Remanufacturing supply chain management

To enhance environmental sustainability and develop circular economy, one of effective methods is to focus on green design of new products, which relates to green investment strategy [7], clean technology adoption [34], production line design [35], and downstream retailing competition [13]. To promote the sale of green products, Shen *et al.* [32] studied the optimal selling sequence of green products *via* a Bayesian demand information updating technology, while Shen *et al.* [33] investigated optimal pricing and advertising decisions for green products in the presence of a non-green product substitute. Another mainstream method for achieving sustainability and circular economy is to operate a profitable remanufacturing business, which depends on product design and remanufacturing mode choice.

The remanufacturing profitability relates to product design, because it is costly to reuse used items from equipment not designed for remanufacturing [45]. Through qualitative data analysis methods, Kerr and Ryan [17] also experimentally suggested that the product design is an important factor for remanufacturing. Therefore, one major research area of remanufacturing supply chain management is to examine the product design for remanufacturing [5, 9, 31, 45, 55]. Wu [46], Wu [45], and Cheng *et al.* [5] stated that the high interchangeability design can lower the production costs for both new and remanufactured products, which intensifies the price competition between OEM and remanufacturer. Reimann *et al.* [31] indicated that the variable remanufacturing cost can be decreased *via* process innovation, and counterintuitively found that the decentralized supply chain can dominate the centralized supply chain if the process innovation cost is high enough. Zhao *et al.* [55] suggested that a choice of higher quality can increase the perceived value of new products, whereas it can also raise the production costs of new and remanufactured products. The above studies considered product design can only have a unilateral effect (*i.e.*, either production cost savings or quality improvement), without considering the possible dual role of product design in terms of demand growth and cost savings. In addition to generating higher demand, the modular design of MC products can retain a highly salvageable value from returns [27], lead to a higher interchangeability degree [46], and thus reduce the remanufacturing cost [4].

Another stream of remanufacturing research is based on the scenarios that the manufacturer, the supplier and the third-party remanufacturer undertake the remanufacturing activity. Xiong *et al.* [47] analyzed and compared the implications of manufacturer-remanufacturing mode and supplier-remanufacturing mode, and discussed the conditions for the manufacturer and the supplier to engage in remanufacturing. Since the remanufactured products provided by third-party remanufacturer would cannibalize the new product sales of manufacturer [30], Zhou *et al.* [57] and Zhou *et al.* [58] suggested that remanufacturer and the manufacturer can cooperatively undertake remanufacturing activity in a novel way: technology licensing. The above-mentioned studies ignore the important role of retailer in a closed-loop system. Due to the advantages of being close to consumer market for offline traditional resellers [51] and the ability of inspecting secondhand products quality for online retailing platforms [36], the retailers may operate and develop the remanufacturing activity [31, 54]. Furthermore, the modular architecture design of MC products has advantages in increasing the remanufacturing profitability, which enables MC retailers to actively operate the remanufacturing business. This paper combines the retailer-remanufacturing mode with the product design for remanufacturing under MC, focusing on investigating the conditions for the upstream MC manufacturer and the downstream brand retailer to undertake the remanufacturing of used MC products, along with examining the impacts of modular design on individual decisions, which provides some insights on how to improve the profitability of remanufacturing MC supply chain.

3. The model

Modular architecture design can not only increase the product variety and thus make MC implementation easier, but also improve interchangeability and then lower the remanufacturing cost. Motivated by this, we consider a remanufacturing MC supply chain consisting of one manufacturer and one retailer, in which the manufacturer designs and then sells the new, modular MC products *via* its brand retailer, meanwhile the remanufacturing of used MC products would be done by either the manufacturer or the retailer. As shown in Figure 1, this paper develops one centralized and two decentralized supply chain decision models: (a) the centralized decision model without double marginal effect, named Model C, which acts as a benchmark of the decentralized models; (b) the manufacturer-remanufacturing decision model, named Model M; (c) the retailer-remanufacturing decision model, named Model R. For all decentralized decision models, the equilibrium/optimal solutions are derived *via* the manufacturer led Stackelberg game, wherein the manufacturer makes decisions first and then the retailer decides later. In the extension section, we further consider the retailer led Stackelberg game scenario for verifying the robustness. All supply chain members are risk neutral and aim to maximize their own profits.

The following subsections present the model construction. First, the cost structure and demand functions are derived in Subsections 3.1 and 3.2, respectively. Then, one centralized model and two decentralized models are orderly formulated in subsequent subsections.

3.1. Cost structure

The essence of MC is product modularity. Before offering MC products, the MC manufacturer needs to invest in the modular design, which breaks down the complex product into many submodules that can be easily assembled into a variety of final products. Following Guo and Liu [9] and Liu *et al.* [24], we use the modularity level m to denote the modular design outcome for MC products. The investment cost of modular design is

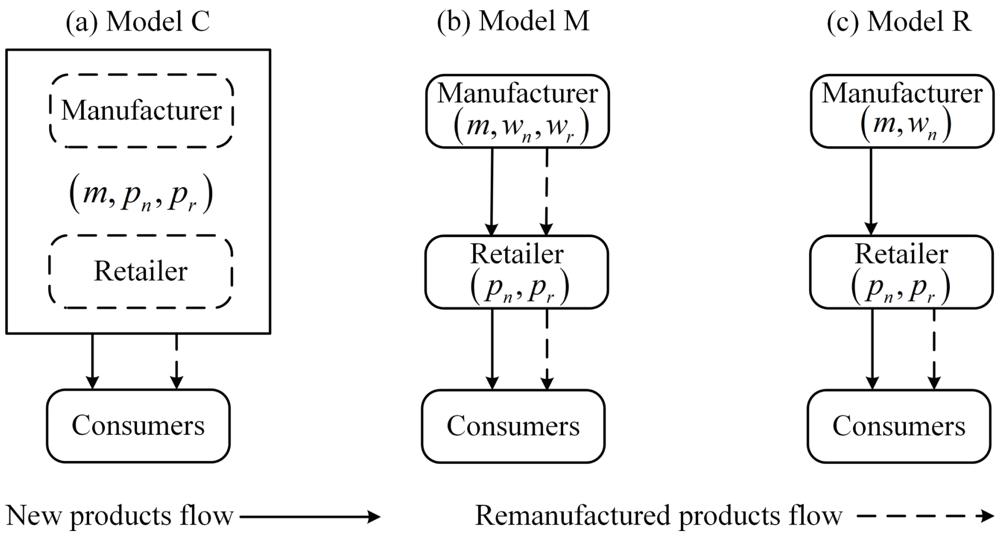

FIGURE 1. Proposed three remanufacturing models under MC.

quadratic in m, *i.e.*, $c_L = \frac{km^2}{2}$ [27, 41], where k is the sensitive parameter. Meanwhile, since the increasing modularity level would lead to an increase in production complexity, the MC manufacturer also needs to bear the new-product unit production cost, which consists of a modularity-related variable cost and a fixed cost unrelated to modularity, *i.e.*, $c_n = cm + c_0$ [21], where $c > 0$ is the unit variable cost and c_0 is the fixed cost. Without loss of generality, we let $c_0 = 0$ to simplify the model. When the products architecture are highly modular, a returned and used MC product can be easily disassembled into multiple useful components that can be built into the new MC products, and then reduces the remanufacturing cost of used MC products [4]. Thus, compared with the new-product production cost c_n, the remanufacturer (*i.e.*, the manufacturer or the retailer) can bear a lower production cost for unit remanufactured MC product, that is, $c_r = c_n - vm$ [15, 44]. vm can be explained as the modularity-related remanufacturing cost savings, which increases in m, and $v > 0$ is the unit cost savings caused by modular design.

3.2. Demand and consumer surplus

The total market size is normalized to 1 [3, 43]. A higher level of modular design can better accommodate consumer's individual needs and then improve customer satisfaction [21, 40], which means that consumer tends to obtain a higher utility at a higher modularity level m. As a result, from one MC product with modularity level m, the θ-type consumer can get a utility θm increasing along with m. Parameter θ is the heterogeneous consumers' willingness-to-pay (WTP) for the new MC products with modularity level m and uniformly distributed in the interval $[0, 1]$; correspondingly, the WTP for the remanufactured MC products is a fraction $\delta \in (0, 1)$ of that for the new ones, denoted as $\delta\theta$ [30, 46]. Meanwhile, because the consumer's utility is also sensitive to the retail price, given the new MC products price p_n and the remanufactured MC products price p_r, the net utility that θ-type consumer can obtain by purchasing one new and remanufactured MC product are $U_n = \theta m - p_n$ and $U_r = \delta\theta m - p_r$, respectively. To ensure that the price of remanufactured products is not so high that no consumers buy them, prices are constrained to satisfy $p_r < \delta p_n$ [2, 57]. A consumer will buy the remanufactured products if $U_r > 0$ and $U_r > U_n$, and thus the market demand for remanufactured MC products is $q_r = \int_{\frac{p_r}{\delta m}}^{\frac{p_n - p_r}{(1-\delta)m}} 1 d\theta = \frac{p_n - p_r}{(1-\delta)m} - \frac{p_r}{\delta m}$. Conversely, a consumer will purchase the new products if $U_r < U_n$, and then the demand for new MC products is $q_n = \int_{\frac{p_n - p_r}{(1-\delta)m}}^{1} 1 d\theta = 1 - \frac{p_n - p_r}{(1-\delta)m}$. We assume that new products have been sold over many periods and there exists abundant used products for remanufacturing [55, 57], which means that the quantity of remanufactured

TABLE 1. Model notations.

Notations	Descriptions
m	Modularity level (decision variable)
w_n/w_r	Wholesale price of new/remanufactured products (decision variable)
p_n/p_r	Retail price of new/remanufactured products (decision variable)
q_n/q_r	Demand or production of new/remanufactured products
θ	Consumer's WTP for the new products with unit modularity level
δ	Consumer's value discount for remanufactured products
c_L	Investment cost of modular design
c_n/c_r	Unit production cost for new/remanufactured products
k	Cost coefficient for the modular design investment
c	Unit variable cost associated with modularity level
v	Unit cost saving from remanufacturing *via* modular design
CS	Consumer surplus
π_i^j	Profit of supply chain member i in model j, where subscript $i = \{m, r, t\}$ represents the manufacturer, retailer, and total supply chain, respectively; superscript $j = \{C, M, R\}$ denotes the different remanufacturing models

MC products will not be constrained by the core supply of used MC products. Following Yenipazarli [48] and Liu *et al.* [25], the consumer surplus can be formulated by $CS = \int_{\frac{p_r}{\delta m}}^{\frac{p_n - p_r}{(1-\delta)m}} (\delta\theta m - p_r)d\theta + \int_{\frac{p_n - p_r}{(1-\delta)m}}^{1} (\theta m - p_n)d\theta$, which can be rewritten as $CS = \frac{(1-\delta)(\delta m(m-2p_n)+p_r^2)+\delta(p_n-p_r)^2}{2\delta m(1-\delta)}$. The key notations and corresponding descriptions are summarized in Table 1.

3.3. Model C: centralized system

As a benchmark case, the integrated supply chain model (Model C) can will provide us with the optimal decisions of supply chain, as all decisions are fully coordinated without the double marginal effect in this case. Dell products and sells customized computers directly to consumers *via* its online store, and also establishes a separate web site to sell its remanufactured computers directly to consumers. This is an example of Model C, where firms offer new or remanufactured MC products directly to consumers without the double marginal effect caused by wholesale prices. As presented in Figure 1a, the manufacturer and the retailer behave as a whole and there is only one decision maker under Model C, in which the modularity level m, the retail price of new MC products p_n, and the retail price of remanufactured MC products p_r are simultaneously decided to maximize the total supply chain profit. The objective function in Model C can be formulated as follows.

$$\max_{m,p_n,p_r} \pi_t^C = (p_n - c_n)q_n + (p_r - c_r)q_r - c_L. \tag{1}$$

In above objective function, the first item $(p_n - c_n)q_n$ can be interpreted as net profit from producing and selling new MC products; the second item $(p_r - c_r)q_r$ is the net profit from producing and selling remanufactured MC products; the third item c_L is the investment cost of modular design before providing MC products. Solving the first-order conditions, the optimal solutions in Model C can be derived, denoted by m^{C*}, p_r^{C*}, and p_n^{C*}. Plugging the optimal solutions into equation (1), we can obtain the equilibrium profit of supply chain under Model C π_t^{C*}. Hereafter, superscript $*$ represents the equilibrium solution. All results are summarized in Table 2.

3.4. Model M: manufacturer-remanufacturing mode

In Model M, the manufacturer also remanufactures used MC products in addition to designing and manufacturing new MC products, while the retailer is only in charge of purchasing and reselling the new and remanufactured MC products, as shown in Figure 1b. An example of Model M is BMW, which offers customized service

TABLE 2. Equilibrium solutions of proposed models.

	Model C	Model M	Model R
m^*	M_1	M_2	M_3
w_n^*	N/A	$\frac{1+c}{2}M_2$	$\frac{1+2c-\delta-v}{2}M_3$
w_r^*	N/A	$\frac{\delta+c-v}{2}M_2$	N/A
p_n^*	$\frac{1+c}{2}M_1$	$\frac{3+c}{4}M_2$	$\frac{3+2c-\delta-v}{4}M_3$
p_r^*	$\frac{\delta+c-v}{2}M_1$	$\frac{3\delta+c-v}{4}M_2$	$\frac{\delta+c-v}{2}M_3$
q_n^*	$\frac{1-\delta-v}{2(1-\delta)}$	$\frac{1-\delta-v}{4(1-\delta)}$	$\frac{1-\delta-v}{4(1-\delta)}$
q_r^*	$\frac{v-(1-\delta)c}{2\delta(1-\delta)}$	$\frac{v-(1-\delta)c}{4\delta(1-\delta)}$	$\frac{(1-\delta)(\delta-2c)+v(2-\delta)}{4\delta(1-\delta)}$
π_m^*	N/A	$\frac{k}{2}(M_2)^2$	$\frac{k}{2}(M_3)^2$
π_r^*	N/A	$\frac{k}{2}(M_2)^2$	$\frac{(1-\delta-v)^2Y}{128k\delta(1-\delta)^2}$
π_t^*	$\frac{k}{2}(M_1)^2$	$k(M_2)^2$	$\frac{(1-\delta-v)^2(\delta(1-\delta-v)^2+Y)}{128k\delta(1-\delta)^2}$
CS^*	$\frac{k}{2}(M_1)^2$	$\frac{k}{4}(M_2)^2$	$\frac{(1-\delta-v)^2Y}{256k\delta(1-\delta)^2}$

Notes. $M_1 = \frac{((1-\delta)(\delta+c^2-2\delta c-2cv)+v^2)}{4\delta k(1-\delta)}$, $M_2 = \frac{((1-\delta)(\delta+c^2-2\delta c-2cv)+v^2)}{8\delta k(1-\delta)}$, $M_3 = \frac{(1-\delta-v)^2}{8k(1-\delta)}$, and $Y = (1-\delta)(\delta(1-v-c) + (3\delta+4v-4c)(\delta+v-c)) + \delta v^2$.

of interior design to consumers *via* its downstream distributor and also operates a remanufacturing gearbox factory. In Model M, the manufacturer that as a leader first determines modularity level m, the wholesale price of new MC products w_n, and the wholesale price of remanufactured ones w_r. Base on the MC manufacturer's decisions, the retailer chooses the corresponding retail price for new and remanufactured products, *i.e.*, p_n and p_r. Aiming at maximizing their own profits, the objective functions for the manufacturer and the retailer in Model M can be expressed as follows, respectively.

$$\max_{m,w_n,w_r} \pi_m^M = (w_n - c_n)q_n + (w_r - c_r)q_r - c_L. \tag{2}$$

$$\max_{p_n,p_r} \pi_r^M = (p_n - w_n)q_n + (p_r - w_r)q_r. \tag{3}$$

In the manufacturer's objective function, the first two items, *i.e.*, $(w_n - c_n)q_n$ and $(w_r - c_r)q_r$, are the net profit from manufacturing and then distributing the new and remanufactured MC products, respectively. The meaning of third item remains the same. In the retailer's objective function, $(p_n - w_n)q_n$ and $(p_r - w_r)q_r$ are the net profit of purchasing and reselling the new as well as remanufactured MC products, respectively. By backward induction method, we can obtain the optimal solutions in Model M, denoted as m^{M*}, w_n^{M*}, w_r^{M*}, p_n^{M*}, and p_r^{M*}. Substituting above optimal solutions into equations (2) and (3), the equilibrium profits for the manufacturer and the retailer in Model M can be obtained, denoted by π_m^{M*} and π_r^{M*}, respectively. Then, the total supply chain profit in Model M will be given by $\pi_t^{M*} = \pi_m^{M*} + \pi_r^{M*}$.

3.5. Model R: retailer-remanufacturing mode

As shown in Figure 1c, under Model R, the remanufacturing activity of used MC products is conducted by the retailer. Apple sells the personalized computers and Apple Watch Band available to consumers through JD and Amazon, while JD and Amazon separately launch Paipai and Amazon Renewed program for producing and selling the remanufactured products. This is an example of Model R, where downstream retailer not only resells new MC products provided by upstream manufacturer but also produces and sells the remanufactured ones. The game timing of Model R is as follows: as a leader, the manufacturer first decides the modularity level m along with the wholesale price of new MC products w_n; then, according to the manufacturer's decisions, the retailer chooses the corresponding retail prices for new and remanufactured MC products, *i.e.*, p_n and p_r.

With the goal of profit maximization, the objective functions for both supply chain members in Model R can be formulated as follows, respectively.

$$\max_{m,w_n} \pi_m^R = (w_n - c_n)q_n - c_L. \tag{4}$$

$$\max_{p_n,p_r} \pi_r^R = (p_n - w_n)q_n + (p_r - c_r)q_r. \tag{5}$$

For the retailer's objective function, the second item $(p_r - c_r)q_r$ represents the net profit from producing and selling the remanufactured MC products. The other items remain the same meaning. Through inverse induction method, the optimal solutions for Model R can be derived, that is, m^{M*}, w_n^{M*}, p_n^{M*}, and p_r^{M*}. Similarly, by substituting these optimal solutions into equation (4) and (5), we can obtain the equilibrium profits of the manufacturer and the retailer, *i.e.*,π_m^{R*} and π_r^{R*}. Finally, the total supply chain profit in Model R can be calculated as $\pi_t^{R*} = \pi_m^{R*} + \pi_r^{R*}$.

4. Equilibrium analysis

In this section, the equilibrium solutions among different remanufacturing models are compared and analyzed, and the optimal remanufacturing mode will be discussed so that the MC supply chain can make corresponding choices. In addition, the special impact of modularity level on remanufacturing MC supply chain is further explored to provide relevant suggestions. Analysis results are concluded in following lemmas and corollaries.

Lemma 4.1. *By comparing different remanufacturing models, the modularity level is related as follows:* $m^{C*} > m^{M*} > m^{R*}$.

Lemma 4.1 shows that the modularity level is the highest in Model C, and that is higher in Model M than in Model R. The higher modularity level for MC products, the easier to assemble and disassemble components and the more diverse the assembled products. Therefore, it is easier for MC firms to meet the customized needs of consumers under higher modularity level. The centralized system is fully coordinated without double marginal effect, and thus performs best among the proposed models, which indicates that the ability to cope with customers customization needs, *i.e.*, the modularity level, can be highest in Model C. Note that, more investment in modular design can not only increase the product variety and thus make MC implementation easier, but also lower the remanufacturing cost. In Model M, the manufacturer operates the remanufacturing business and thus benefits from the remanufacturing cost savings caused by the modular architecture design. In Model R, however, the remanufacturing cost savings related to modular design directly benefits the free-riding retailer since the remanufacturing business is operated by the retailer in this case. As a result, the MC manufacturer tends to invest more in modular design under Model M than Model R, which leads to a higher modularity level in Model M compared to Model R. In actual operation, for the higher modularity level of MC products, *i.e.*, better customized service, the supply chain should assign the manufacturer to remanufacture the end-of-use MC products.

Lemma 4.2. *By comparing different remanufacturing models, the retail price and demand for new MC products are related as follows:*

(a) $p_n^{C*} > p_n^{M*} > p_n^{R*}$*; (b)* $q_n^{C*} > q_n^{M*} = q_n^{R*}$.

For new MC products, Lemma 4.2 shows that the retail price and demand are highest in Model C. Moreover, the retail price in Model M is higher in comparison to Model R, whereas the demand for both models is same. Higher modularity level means larger modular design investment cost based on the characteristics of investment cost (*i.e.*, c_L). Thus, referring to Lemma 4.1, the investment cost is highest in Model C, and this cost is higher in Model M than Model R. In order to make up for the largest investment cost, the retail price of new MC products tends to be set highest in Model C, whereas the demand of new MC products can keep the highest in Model C due to the best customized service (*i.e.*, highest modularity level) even if consumers need to pay an extra price. Compared to Model R, the manufacturer in Model M would choose higher wholesale price for new MC products (*i.e.*, $w_n^{M*} > w_n^{R*}$) to cover the higher investment cost, which results in higher retail price. For consumers under Model M, the positive effect of higher modularity level offsets the negative utility of higher retail price compared to Model R, which leads to the same demand for new MC products in both models. In practice, to pursue higher marginal profits from new MC products (*i.e.*, higher retail price) without compromising market demand, the supply chain should give priority to the situation where the manufacturer remanufactures the used MC products.

Lemma 4.3. *By comparing different remanufacturing models, the retail price and demand for remanufactured MC products are related as follows, respectively:*

(a) if $v < \frac{\delta+3c}{3}$, $p_r^{C*} > p_r^{M*} > p_r^{R*}$*; otherwise,* $p_r^{M*} > p_r^{C*} > p_r^{R*}$.
(b) $q_r^{R*} > q_r^{C*} > q_r^{M*}$.

As shown in Lemma 4.3a, in a comparison of Model C and Model M, when the parameter v is low (*i.e.*, $v < \frac{\delta+3c}{3}$), the retail price for remanufactured MC products is higher in Model C; otherwise, the retail price is higher in Model M. Additionally, the retail price of remanufactured MC products is always the lowest in Model R. The reasons are as follows. Low v means that the remanufacturing cost savings caused by modular design is at a low level and then the production cost of remanufacturing used MC products is high. Under this case, aiming to make up for the large marginal production cost as well as the modular design investment cost, the centralized supply chain (*i.e.*, Model C) can directly set a higher retail price for remanufactured MC products, so as to gain more marginal profits. In the decentralized supply chain (*i.e.*, Model M), however, both costs can be shared between the manufacturer and the retailer, without setting a higher retail price. When v is high enough, the remanufacturing cost savings from modular design is at a high level, which allows the centralized supply chain to directly set a low retail price for remanufactured MC products. Nevertheless, differ from the centralized supply chain, the benefit of remanufacturing cost savings would be shared between two supply chain members in Model M, which discourages Model M from charging lower retail price than Model C. Additionally, in Model R where the retailer operates the remanufacturing business of used MC products, the remanufacturing cost savings related to modular design only benefits the retailer without bearing any investment cost of modular design. This enables the free-riding retailer to set a lowest price for remanufactured MC products in Model R.

We counterintuitively find from Lemma 4.3b that, the remanufactured MC products demand in a decentralized system where the retailer remanufactures the used MC products (*i.e.*, Model R) can exceed that in the centralized system where all decisions are fully coordinated (*i.e.*, Model C), *i.e.*, $q_r^{R*} > q_r^{C*}$. For the consumers who purchase the remanufactured products, they are more sensitive to price than quality. Meanwhile, the retail price of remanufactured MC products in Model R is the highest among proposed models, which results in the highest demand in Model R. Therefore, to capture larger remanufactured MC products market, it is better for supply chain to assign the retailer to remanufacture the used MC products in practice.

Corollary 4.4. *When the modularity level is exogenous, the impacts of modularity level on wholesale price and retail price for new and remanufactured MC products are respectively shown as follows:*

(a) $\frac{\partial w_n^{M*}}{\partial m} > \frac{\partial w_n^{R*}}{\partial m} > 0$ *and* $\frac{\partial p_n^{M*}}{\partial m} > \frac{\partial p_n^{R*}}{\partial m} > \frac{\partial p_n^{C*}}{\partial m} > 0$.
(b) $\frac{\partial w_r^{M*}}{\partial m} > 0$ *and* $\frac{\partial p_r^{M*}}{\partial m} > \frac{\partial p_r^{R*}}{\partial m} > \frac{\partial p_r^{C*}}{\partial m} > 0$.

For new and remanufactured MC products in the proposed models, Corollary 4.4 suggests that the wholesale price and retail price both increase along with the modularity level. As the modularity level increases, the MC manufacturer has to bear more investment cost due to the characteristic of the modular design cost function (*i.e.*, km^2). Therefore, in order to make up for this increased investment cost, the manufacturer in decentralized supply chain tends to charge a larger wholesale price for more marginal profits (*i.e.* $\frac{\partial w_n^{M*}}{\partial m} > 0$, $\frac{\partial w_n^{R*}}{\partial m} > 0$, $\frac{\partial w_r^{M*}}{\partial m} > 0$), which in turn stimulates the retailer to set a higher retail price ($i.e.$ $\frac{\partial p_n^{M*}}{\partial m} > 0$, $\frac{\partial p_n^{R*}}{\partial m} > 0$, $\frac{\partial p_r^{M*}}{\partial m} > 0$). In contrast, without adjusting the wholesale price, the centralized supply chain can directly choose a higher retail price to compensate for the increased modular investment cost ($i.e.$ $\frac{\partial p_n^{C*}}{\partial m} > 0$, $\frac{\partial p_r^{C*}}{\partial m} > 0$). The increasing modularity level can create higher demand because of higher consumer's utility, which allows the retailer who conducts the remanufacturing activity to increase the retail price for remanufactured MC products ($i.e.$ $\frac{\partial p_r^{R*}}{\partial m} > 0$). Additionally, Corollary 4.4 also implies that the pricing decisions of Model M is more sensitive to the changes in the modularity level, which is beneficial for the supply chain to make corresponding decisions in time. Thus, considering the decision-making speed in practice, the supply chain ought to prioritize the scenario that the manufacturer remanufactures the used MC products.

Lemma 4.5. *By comparing different remanufacturing models in decentralized systems, the profits for the manufacturer and the retailer are related as follows, respectively:*

(a) $\pi_m^{M*} > \pi_m^{R*}$.

(b) if $c > c_1(v,\delta)$, $\pi_r^{R*} > \pi_r^{M*}$; *otherwise,* $\pi_r^{M*} > \pi_r^{R*}$, *where* $c_1(v,\delta) = \frac{(1-\delta)(\delta+v)-\sqrt{2\delta(1-\delta)(1-\delta-v)^2}}{1-\delta}$.

As indicted in Lemma 4.5, the manufacturer prefers the scenario that the used MC products are remanufactured by itself since its profit is higher in Model M than Model R. Moreover, only if c is high, $i.e.$, $c > c_1(v,\delta)$, the retailer prefers to remanufacture the used MC products since a higher profit can be obtained in Model R compared to Model M; otherwise, the retailer prefers the manufacturer-remanufacturing mode.

Note that, before providing MC products, the manufacture needs to invest in modular architecture design, which can not only make MC occur easier but also save more remanufacturing cost. When the used MC products is remanufactured by the manufacturer ($i.e.$, Model M), the manufacturer can utilize the benefits from the remanufacturing cost savings to compensate for the modular investment cost, thereby improving the profitability of the manufacturer in Model M. Additionally, high c means that the unit production cost associated with modularity level is large, the manufacturer who operates remanufacturing business tends to share this cost with the retailer *via* adjusting the wholesale price of remanufactured MC products. This enhances the double marginal effect and then decreases the retailer's profit in Model M. When the retailer undertakes the remanufacturing (*i.e.,* Model R), however, the double marginal effect caused by the wholesale price of remanufactured MC products can be effectively avoided, which creates a higher profit for the retailer in Model R. Therefore, in actual operation, when the unit production cost associated with modularity level is low, the supply chain should prioritize the scenario where the manufacturer remanufactures used MC products since the manufacturer and the retailer both prefer this scenario.

Lemma 4.6. *By comparing different remanufacturing models, the total supply chain profit and consumer surplus are related as follows, respectively:*

(a) $\pi_t^{C*} > \pi_t^{M*} > \pi_t^{R*}$.
(b) if $c < c_1(v,\delta)$, $CS^{C*} > CS^{M*} > CS^{R*}$; *otherwise,* $CS^{C*} > CS^{M*}$, $CS^{R*} > CS^{M*}$.

As shown in Lemma 4.6a, the total supply chain profit in Model C is the highest because all decisions are centrally coordinated in this situation. In comparison of two decentralized remanufacturing modes, the intuitive view is that, when the retailer produces and sells the remanufactured MC products directly to consumers ($i.e.$, Model R), the double marginal effect caused by the transfer price of remanufactured products ($i.e.$, the wholesale price in Model M) can be avoided, thereby generating a higher efficiency for supply chain in Model R than in Model M. However, we surprisingly find from Lemma 4.6a that, the total supply chain profit is higher in Model M than Model R. The main reason is as follows. Compared to Model R, the modularity level is higher in Model M ($i.e.$, see Lem. 4.1), which creates a better ability coping with consumer customization requirements and a larger remanufacturing cost savings for Model M. Meanwhile, as presented in Lemmas 4.2a and 4.3a, the

TABLE 3. Summary of parameters setup.

Parameters	Ranges
c	0.3,0.35,...,0.6
δ	0.3,0.35,...,0.6
v	0.2,0.25,...,0.5
k	1

retail prices for new and remanufactured MC products in Model M exceed those in Mode R, which brings more marginal profits for Model M. As a result, the supply chain can gain more profit in Model M than in Model R.

Additionally, we find from Lemma 4.6b that, if c is low, *i.e.*, $c < c_1(v, \delta)$, Model R is the least desirable for consumers since the consumer surplus in Model R is the lowest among proposed models; otherwise, Model M is the least desirable. Therefore, in the actual operation, for higher total supply chain profit, the supply chain ought to choose the manufacturer to act as the remanufacturer of used MC products. For more consumer welfare, if the unit production cost associated with modularity level is low, the supply chain should choose the manufacturer as the remanufacturer of used MC products; otherwise, the supply chain should choose the retailer as the remanufacturer.

Corollary 4.7. *When the modularity level is exogenous, the impact of modularity level on consumer surplus is shown as follows:* $\frac{\partial CS^{C*}}{\partial m} > \frac{\partial CS^{R*}}{\partial m} > \frac{\partial CS^{M*}}{\partial m} 0$.

As indicated in Corollary 4.7, when the modularity level is exogenously given, the consumer surplus increases with the modularity level among different remanufacturing modes. As the modularity level increases, the product variety increases and then the ability to cope with consumer customized needs can be improved, which generates more consumer welfare. Thus, in a remanufacturing MC supply chain, more investment in modular design cannot only make MC take place easier along with saving more remanufacturing cost for remanufacturers, but also create larger welfare for consumers. By comparing two decentralized remanufacturing modes, we find from Corollary 4.7 that, the consumer surplus is more sensitive to the change of modularity level in Model R than Model M, due to the advantage of the retailer's proximity to consumers. From Corollarys 4.4 and 4.7, the optimal pricing and consumer surplus both increase along with the modularity level. This implies that, *via* increasing the modularity level, the remanufacturing MC supply chain is able to charge higher prices for more marginal revenue without sacrificing consumer welfare.

5. NUMERICAL ANALYSIS

In this section, the modularity level, the manufacturer's profit, the retailer's profit, total supply chain profit, and consumer surplus among different remanufacturing models are numerically compared and analyzed, respectively. The numerical analysis is performed by varying: (a) the modularity-related unit production cost c, which is the key factor in MC production process; (b) the value discount for remanufactured MC products δ that reflects consumer preference for remanufactured products compared to new ones; (c) the unit remanufacturing cost saving v caused by the modular architecture design. Referring to Mukhopadhyay and Setoputro [27] and Reimann *et al.* [31], the values of parameters are set as follows: (a) when analyzing the impact of c, then $c \in \{0.3, 0.35, \ldots, 0.6\}$ and other parameters are fixed as $\delta = 0.5$, $v = 0.3$, and $k = 1$; (b) when analyzing the impact of δ, then $\delta \in \{0.3, 0.35, \ldots, 0.6\}$ and other parameters are fixed as $c = 0.4$, $v = 0.3$, and $k = 1$; (c) when analyzing the impact of v, then $v \in \{0.2, 0.25, \ldots, 0.5\}$ and other parameters are fixed as $c = 0.4$, $\delta = 0.5$, and $k = 1$. For clarity, the data set used for numerical analysis is summarized in Table 3.

Before capturing the changes in optimal results with respect to some key parameters, we first provide Table 4 for all optimal results numerically to understand the proposed models briefly, where the values of parameters are fixed as $c = 0.45$, $\delta = 0.5$, $v = 0.3$, and $k = 1$.

TABLE 4. Optimal results numerically of proposed models ($\times 10^{-3}$).

	Model C	Model M	Model R
m^*	54.2	27.1	6.7
w_n^*	N/A	19.6	3.7
w_r^*	N/A	8.8	N/A
p_n^*	39.3	23.4	5.2
p_r^*	17.6	11.2	2.2
q_n^*	200	100	100
q_r^*	150	75	250
π_m^*	N/A	0.55	0.03
π_r^*	N/A	0.55	0.44
π_t^*	2.2	1.1	0.48
CS^*	2.2	0.28	0.22

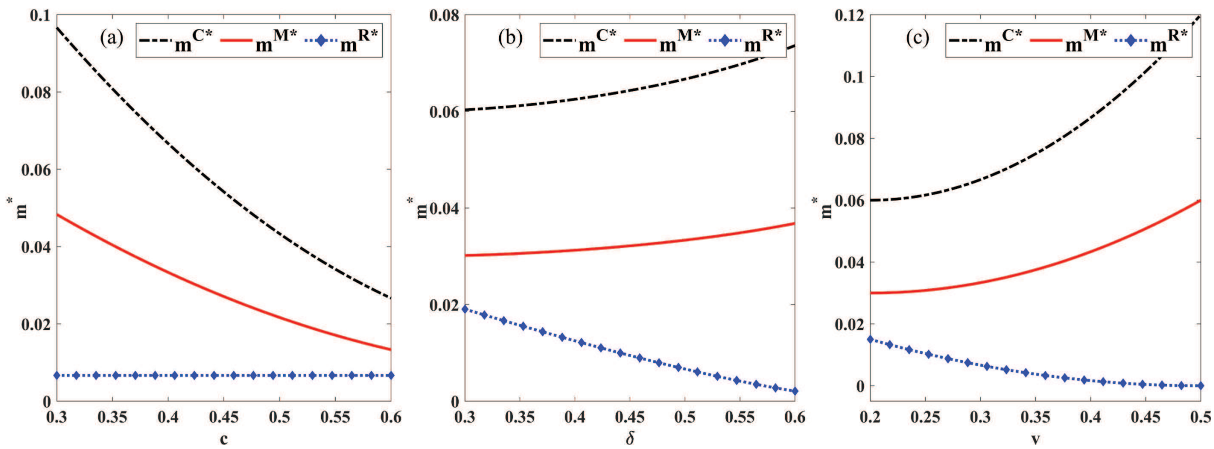

FIGURE 2. Numerical analysis for modularity level.

Some theoretical results can be numerically verified by Table 4. For example, the optimal modularity level and new MC products' retail price are numerically highest in Model C and lowest in Model R among proposed models, which is line with the theoretical results of Lemmas 4.1 and 4.2a. Table 4 also shows that the remanufactured MC products' retail price is numerically lowest in Model R, which is consistent the theoretical results of Lemma 4.3a.

By comparing two decentralized remanufacturing models, we find from Table 4 that, the market demand for new MC products is numerically same in Model M and Model R, while the market demand for remanufactured MC products is numerically higher in Model R, which verifies the theoretical results of Lemmas 4.2b and 4.3b. Compared to Model R, Table 4 also numerically suggests that Model M can generate higher profit for the manufacturer, the retailer, and total supply chain, along with more surplus for consumers. This verifies our main conclusion that the manufacturer-remanufacturing mode can be superior to the retailer-remanufacturing mode, in terms of profit or consumer welfare generation, *i.e.*, Lemmas 4.5 and 4.6.

Figure 2a shows that, as c increases, the modularity level decreases in Model C and Model M since the modularity-related production cost is higher under higher c, whereas it remains unchanged in Model R. Facing the increase of c in Model R, the manufacturer decreases the modularity level for reducing the production cost of new MC products, whereas this also lowers production cost for the retailer who produces remanufactured MC products. Thus, the manufacturer in Model R chooses a modularity level independent of c to deter the

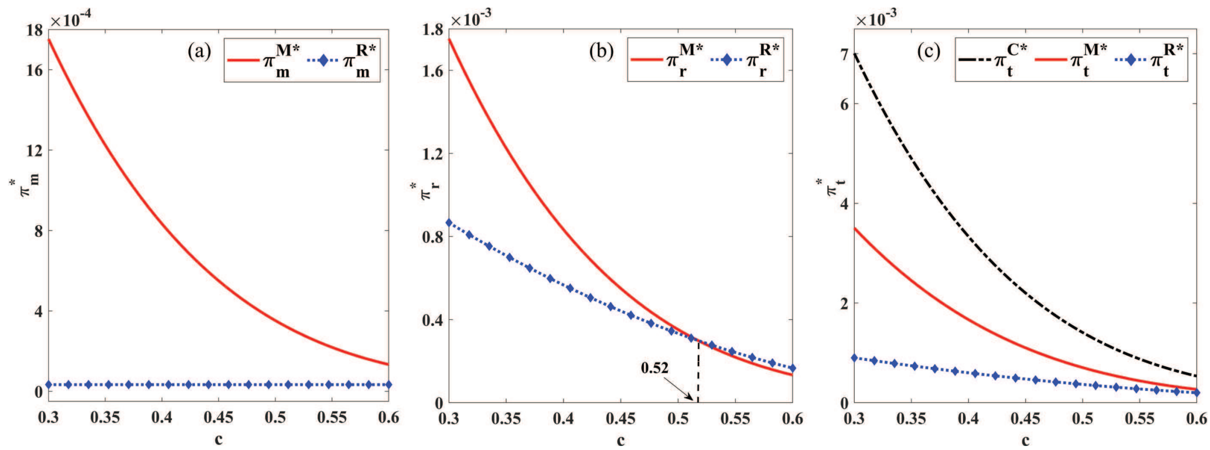

FIGURE 3. Impact of c on supply chain profits.

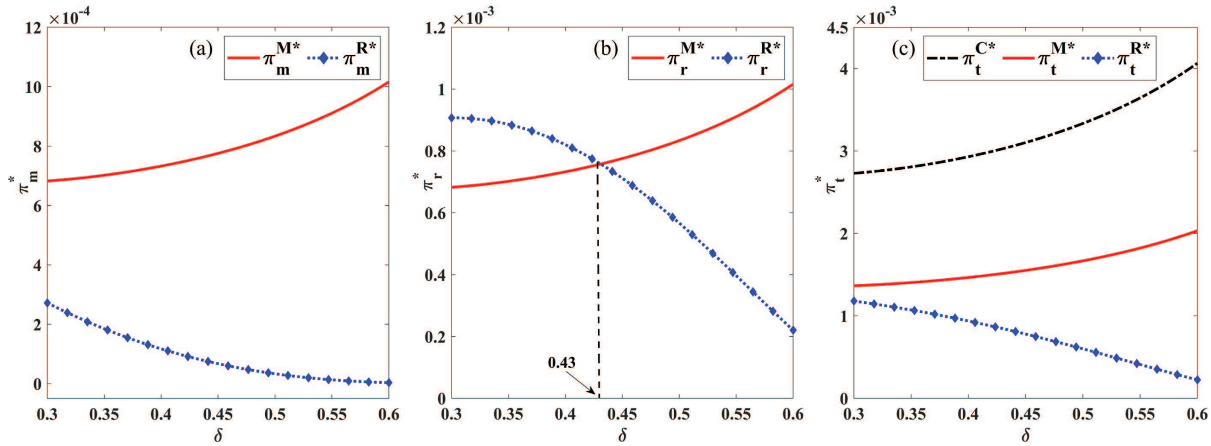

FIGURE 4. Impact of δ on supply chain profits.

free-riding retailer. From Figures 2b and c, as δ and v increase, the modularity level increases in Model C and Model M owing to higher demand income and larger cost savings from the remanufacturing at higher δ and v, but it decreases in Model R due to the free-riding retailer. Figure 2 also suggests that, the modularity level is highest in Model C, while it is higher in Model M than Model R, which verifies Lemma 4.1.

As presented in Figure 3, the profits for the manufacturer, the retailer, and total supply chain in proposed models increase along with c, except that the manufacturer's profit in Model R is independent of c. With higher c, the modularity-related unit production cost for MC products is higher, which hurts the profitability. However, under Model R, the free-riding retailer benefits the remanufacturing cost saving caused by modular design, because the modular MC products are remanufactured by the retailer in Model R. To decrease the cost disadvantage and deter the free-riding retailer, the manufacturer in Model R chooses an optimal modularity level that is no related to c, *i.e.*, Figure 2a, which causes its profitability in Model R being unaffected by c.

Figures 4 and 5 show that, when δ and v increase, the profits for manufacturer, retailer, and total supply chain increase in Model M and Model C, but decrease in Model R. Higher δ implies higher consumer valuation for remanufactured MC products, and thus more consumers are willing to purchase the remanufactured MC

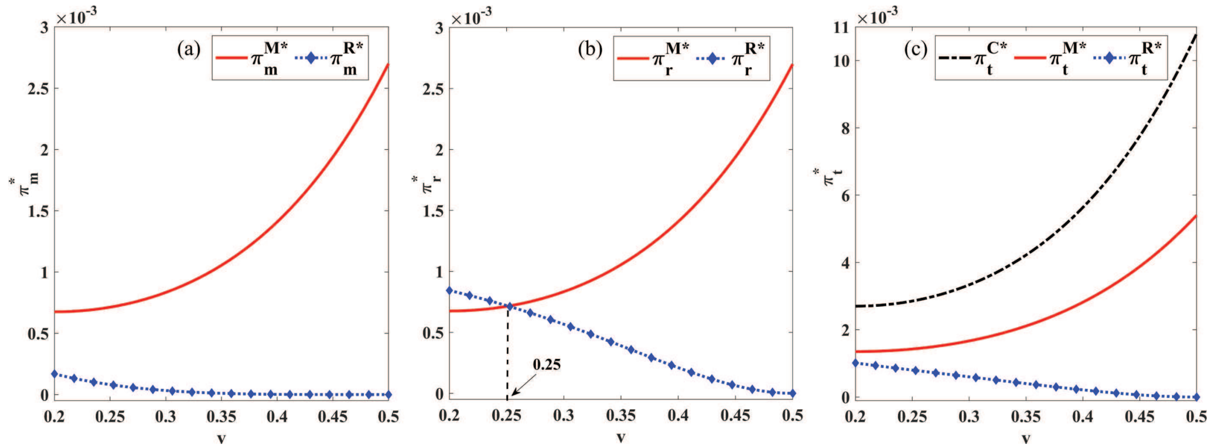

FIGURE 5. Impact of v on supply chain profits.

products under higher δ, which increases the supply chain profits in Model M and Model C. Nevertheless, in Model R, higher δ only benefits the free-riding retailer who produces and sells the remanufactured MC products at lower cost due to highly modular architecture design. This motivates the manufacturer to choose a lower modularity level m under higher δ so as to deter the free-riding retailer, *i.e.*, Figure 2b. As a result, when δ increases in Model R, the ability to respond to customer's customization requirements is diminished because of the lower m, which leads to a decrease in supply chain profitability under Model R as δ increases.

In Model M and Model C, higher v means that modular architecture design of MC products can save larger remanufacturing cost for the manufacturer and total supply chain, who produce both new and remanufactured MC products. This leads to an increase in supply chain profitability under Model M and Model C as v increases. In Model R, the larger modularity-related remanufacturing cost saving caused by higher v is only benefited to the free-riding retailer, who remanufactures the used, modular MC products without bearing the modular design cost. This motivates the manufacturer in Model R to choose a lower modularity level m under higher v for deterring the free-riding retailer, as illustrated in Figure 2c. Therefore, as v increases in Model R, the ability that copes with customer's customization requirements is diminished due to lower m, which in turn hurts the supply chain profitability under Model R. Furthermore, from Figures 3–5a and b, only if c is lower or δ and v are higher (*i.e.*, $c < 0.52$, $\delta > 0.43$, and $v > 0.25$), the manufacturer and the retailer both prefer the manufacturer to remanufacture the used MC products, because their profits are higher in Model M than Model R under this case, which is consistent with the results of Lemma 4.5.

From Figure 6, when the parameter c increases, the consumer surplus decreases in proposed models. Meanwhile, when the parameters δ and v increase, the consumer surplus increases in Model C and Model M, whereas it decreases in Model R. When c increases, the modularity-related variable cost cm increases. In response, if c increases, the modularity level m in Model C and Model M will be set lower to decrease this variable cost, the retail prices for new and remanufactured MC products in Model R will be set higher to make up for the increased variable cost. Then, the consumer surplus among proposed models decreases along with c since lower utility would be obtained under higher c. The increased remanufacturing cost savings from higher v and larger demand revenue of remanufactured MC products from higher δ enable supply chain in Model C and the manufacturer in Model M to invest more in modular design. In Model R, however, the remanufacturing cost savings and demand revenue of remanufactured MC products are only benefited by the retailer, which discourages the manufacturer from choosing a higher modularity level under higher δ and v. Note that, the consumer surplus increases in modularity level, as shown in Corollary 4.7. Therefore, when δ and v increase, the consumer surplus

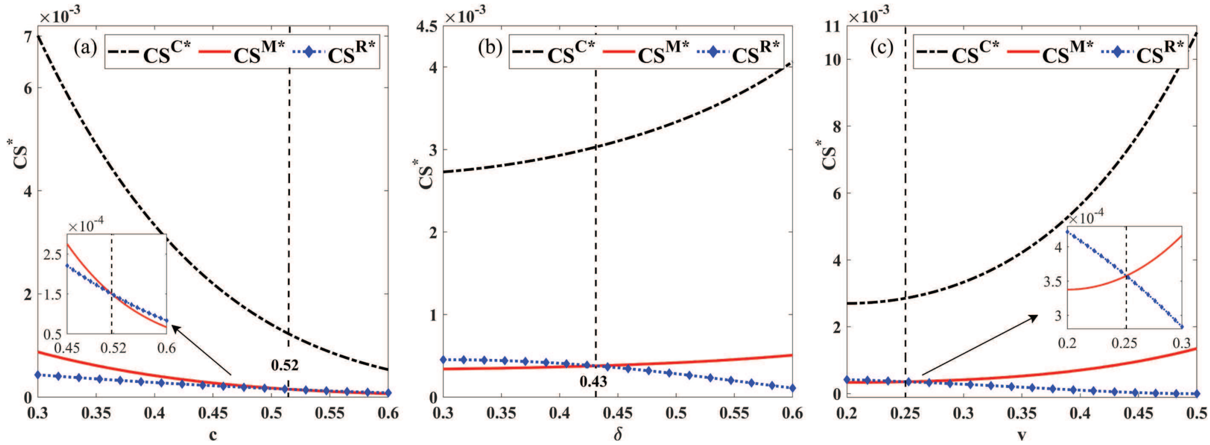

FIGURE 6. Numerical analysis for consumer surplus.

in Model C and Model M would increase due to higher m, and the consumer surplus in Model R decreases due to lower m.

In comparison to Model R, we find from Figure 3–5c that the total supply chain profit is higher in Model M; moreover, there exists a threshold $c_1(v, \delta)$ consisting of v and δ only below which the consumer surplus is higher in Model M (*i.e.*, Fig. 6), which verifies Lemma 4.6.

6. Extension

In this section, in order to verify the robustness of the main findings in base models, we conduct the following two extensions: (1) the remanufacturing is bound by the core supply of used products; (2) the retailer-led Stackelberg game.

6.1. Remanufacturing is bound

In the main models, the used-product quantity is assumed to be abundant for remanufacturing, based on the condition that the new products have been sold over many periods. Aimed at verifying the robustness of our main conclusions, we release this assumption and further consider the case that the remanufacturer's capacity is bounded by the cores supply of used products, *i.e.*, $q_r \leq \tau q_n$, where $0 \leq \tau \leq 1$ means that not all used products can be collected or remanufactured. Following Reimann *et al.* [31] and Xiong *et al.* [47], we let $\tau = 1$ such that significantly simplify the analysis without changing any qualitative insights. In this subsection where the remanufacturing is bound, the profit functions are the same as those in the previously proposed models, except that the constraint condition $q_r \leq q_n$ is added. To differentiate from the base models of unbound remanufacturing, the superscript B is added to represent the extended decision models, in which the remanufacturing activity is bounded by the cores supply of used MC products. To focus on comparing manufacturer-remanufacturing mode with retailer-remanufacturing mode under bound remanufacturing scenario, the idealized benchmark model (*i.e.*, centralized supply chain system without double marginal effect) would not be considered in extension section. As a result, the two decentralized remanufacturing models can be rewritten in this subsection as follows, respectively.

Model BM: manufacturer-remanufacturing mode under bound remanufacturing.

$$\max_{m, w_n, w_r} \pi_m^{BM} = (w_n - c_n)q_n + (w_r - c_r)q_r - c_L,$$

$$s.t.\ q_r \leq q_n.$$

$$\max_{p_n,p_r} \pi_r^{BM} = (p_n - w_n)q_n + (p_r - w_r)q_r.$$

Model BR: retailer-remanufacturing mode under bound remanufacturing.

$$\max_{m,w_n} \pi_m^{BR} = (w_n - c_n)q_n - c_L.$$

$$\max_{p_n,p_r} \pi_r^{BR} = (p_n - w_n)q_n + (p_r - c_r)q_r,$$

$$s.t.\ q_r \le q_n.$$

Using backward induction method, we can derive the equilibrium solutions with bound remanufacturing, and further obtain some insights based on this. If the quantity of used MC products for remanufacturing is limited, the remanufacturer would choose an optimal remanufacturing strategy: full remanufacturing or partial remanufacturing, which leads to two different supply chain operational decisions. Thus, in this case, before analyzing the optimal decisions for a MC supply chain with bound remanufacturing, the remanufacturing strategy for used MC products should be clarified first.

Proposition 6.1. *When the remanufacturing is bound by cores supply of used products, the choice of remanufacturing strategies depends on v: if $v > \frac{(1-\delta)(\delta+c)}{1+\delta}$ under Model BM or $v > (1-\delta)c$ under Model BR, the full remanufacturing strategy is chosen; otherwise, the partial remanufacturing strategy is chosen.*

As suggested in Proposition 6.1, when v is higher, the remanufacturing cost savings caused by MC products modular design is at a higher level, which motivates the remanufacturer to put all used products into remanufacturing (*i.e.*, full remanufacturing strategy) such that benefit more from the remanufacturing activity. Nevertheless, when v is lower, the modular design only creates a lower remanufacturing cost savings, and then remanufacturer puts partial used products into remanufacturing (*i.e.*, partial remanufacturing strategy).

Proposition 6.2. *When the remanufacturing is bound by cores supply of used products, the relationship of modularity level between different remanufacturing modes remains robust, i.e., $m^{BM*} > m^{BR*}$.*

If the remanufactured products production quantity is bound by the cores supply of used products, the remanufacturer tends to choose full or partial remanufacturing strategy. Meanwhile, the supply chain members would choose the appropriate operational decisions (*e.g.*, modular design decision), based on the different remanufacturing strategies. As shown in Proposition 6.2, when the remanufacturing is bound, regardless of the full or partial remanufacturing strategy, the modularity level is always higher in manufacturer-remanufacturing mode than retailer-remanufacturing mode, which is consistent with the unbound remanufacturing scenario (*i.e.*, see Lem. 4.1). The dual benefits of demand growth and remanufacturing cost savings from modular design are only available to the member who remanufactures used MC products, which incentivizes the manufacturer to set a higher modularity level in manufacturer-remanufacturing mode.

We also find from Proposition 6.1 that, when $c < \frac{(1+\delta)v-\delta(1-\delta)}{1-\delta}$ for manufacturer-remanufacturing or $c < \frac{v}{1-\delta}$ for retailer-remanufacturing, the remanufacturer (*i.e.*, manufacturer in Model BM or retailer in Model BR) would choose full remanufacturing strategy; otherwise, the partial remanufacturing strategy would be chosen. As illustrated in Figure 7a, regardless of the full or partial remanufacturing strategy under bound remanufacturing scenario, the profits for manufacturer and total supply chain are always higher in manufacturer-remanufacturing mode than retailer-remanufacturing mode (*i.e.*, $\Delta\pi_m^{B*} = \pi_m^{BM*} - \pi_m^{BR*} > 0$ and $\Delta\pi_t^{B*} = \pi_t^{BM*} - \pi_t^{BR*} > 0$), which maintains the robustness of results in unbound remanufacturing scenario, *i.e.*, Lemmas 4.5a and 4.6a. However, only if the modularity-related unit manufacturing cost c is lower, *i.e.*, $c < c_1(\delta, v)$, Figure 7b shows that the retailer's profit and consumer surplus would be higher in the manufacturer-remanufacturing mode under bound remanufacturing (*i.e.*, $\Delta\pi_r^{B*} = \pi_r^{BM*} - \pi_r^{BR*} > 0$ and $\Delta CS^{B*} = CS^{BM*} - CS^{BR*} > 0$), which is consistent with Lemmas 4.5b and 4.6b wherein the remanufacturing is unbound.

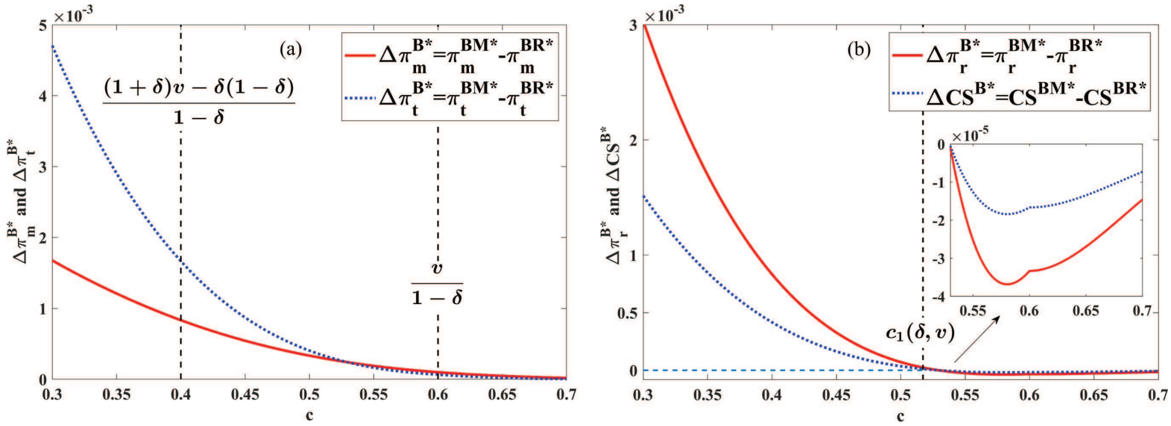

FIGURE 7. Comparison between Model M and Model R under bound remanufacturing ($\delta = 0.5$, $v = 0.3$, $k = 1.5$).

6.2. Retailer leadership

In the base models, we conclude that manufacturing-remanufacturing mode performs better than retailer-remanufacturing mode, with an assumption that manufacturer is a Stackelberg leader and makes decisions first. However, some powerful retailers, such as Walmart and Amazon, tend to be the leader, acting as first movers in announcing prices, so as to better coordinate their product prices and cope with market changes. Aiming to verify the robustness of our main conclusions, this subsection further considers a retailer-leadership scenario, in which the retailer acts a Stackelberg leader and makes retail prices decisions first while the manufacturer is a follower and decides later.

To derive the explicit solution for the optimal modularity level under retailer leadership, the demand for new and remanufactured MC products are respectively simplified as $q_n = 1 - p_n + \beta p_r + m$ and $q_r = 1 - p_r + \beta p_n + m$ [41,50], where β represents the substitute rate between the two types of product. The above-mentioned demand functions without theoretical basis are similar to the demand functions in our base models, wherein the demand for a certain type of product increases with modularity level and price of substitute product, but decreases with its own retail price. In this case, the consumer surplus would be given by $CS = \frac{q_n^2 + q_r^2}{2}$ [49]. For distinguishing it from the base models with manufacturer leadership, the superscript L is added to indicate the extended decision models where the retailer is a Stackelberg leader. Under retailer leadership, the timing for Model M and Model R is as follows: the retailer first decides retail prices, and then the manufacturer sets corresponding wholesale prices and modularity level based on the retailer's decisions. Hence, the objective functions of Model M and Model R under retailer leadership would be rewritten as follows, respectively.

Model LM: manufacturer-remanufacturing mode under retailer leadership.

$$\max_{p_n, p_r} \pi_r^{LM} = (p_n - w_n)q_n + (p_r - w_r)q_r,$$

$$s.t.(m^*, w_n^*, w_r^*) \in \arg \max_{m, w_n, w_r} \pi_m^{LM} = (w_n - c_n)q_n + (w_r - c_r)q_r - c_L.$$

Model LR: retailer-remanufacturing mode under retailer leadership.

$$\max_{p_n, p_r} \pi_r^{LR} = (p_n - w_n)q_n + (p_r - c_r)q_r,$$

$$s.t.(m^*, w_n^*) \in \arg \max_{m, w_n} \pi_m^{LR} = (w_n - c_n)q_n - c_L.$$

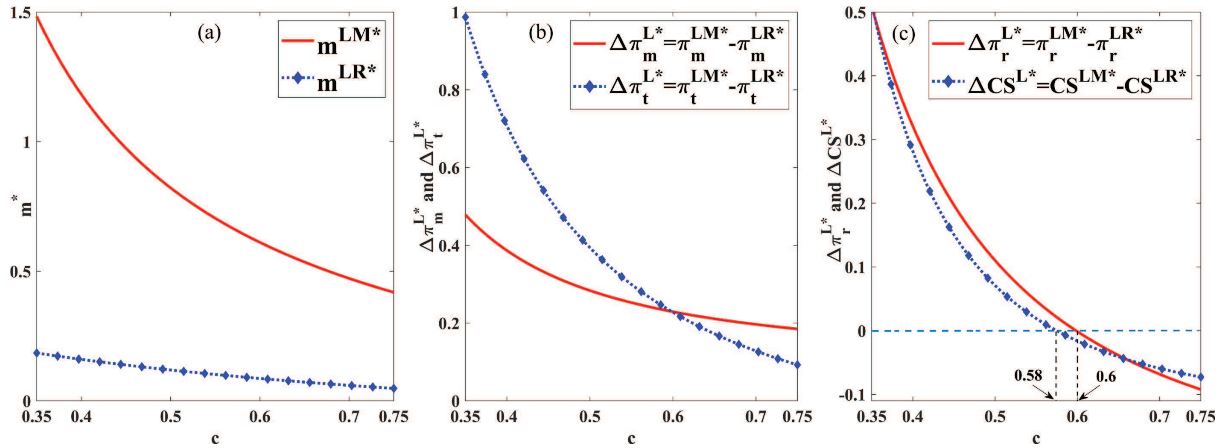

FIGURE 8. Comparison between Model M and Model R under retailer leadership ($\beta = 0.3$, $v = 0.3$, $k = 1.5$).

By backward induction, we can obtain the equilibrium solutions of Model LM and Model LR, which are presented in Appendix. Then, with retailer leadership, we further compare the manufacturer-remanufacturing mode and the retailer-remanufacturing mode, in terms of the modularity level, the manufacturer's profit, the retailer's profit, the total supply chain profit, and the consumer surplus, as illustrated in Figure 8.

When the retailer is the Stackelberg leader, Figure 8a shows that the optimal modularity level is higher in manufacturer-remanufacturing mode than retailer-remanufacturing mode, which is line with the result in Lemma 4.1 where the manufacturer is the leader. As indicated in Figure 8b, under retailer leadership, manufacturer-remanufacturing mode can always generate more profits for manufacturer and total supply chain compared to retailer-remanufacturing mode (*i.e.*, $\Delta\pi_m^{L*} = \pi_m^{LM*} - \pi_m^{LR*} > 0$ and $\Delta\pi_t^{L*} = \pi_t^{LM*} - \pi_t^{LR*} > 0$), which maintains the robustness of the results in Lemmas 4.5a and 4.6a where the manufacturer is the leader.

If the modularity-related unit manufacturing cost c is lower, Figure 8c suggests that manufacturer-remanufacturing mode under retailer leadership can generate higher retailer's profit and more consumer surplus compared to retailer-remanufacturing mode under retailer leadership, *i.e.*, $\Delta\pi_r^{L*} = \pi_r^{LM*} - \pi_r^{LR*} > 0$ if $c < 0.6$ and $\Delta CS^{L*} = CS^{LM*} - CS^{LR*} > 0$ if $c < 0.58$. This is consistent with Lemmas 4.5b and 4.6b where the manufacturer is the leader. As a result, even if the retailer is a Stackelberg leader, manufacturing-remanufacturing mode can also achieve an all-win situation for manufacturer, retailer, total supply chain, and consumers, whereas retailer-remanufacturing mode fail in achieving such a situation. Mian reasons are as follows. In the remanufacturing MC supply chain, whether the manufacturer is a leader or the retailer is a leader, the optimal modularity level is always determined by the manufacturer. Because of the dual effect of modular design of MC products on demand growth and remanufacturing cost saving, the remanufacturing business of used MC products should be operated by the manufacturer, which is independent of who acting as the Stackelberg leader.

7. Conclusions, managerial insights, and future research directions

Motivated by the dual role of product modularity in MC and remanufacturing, this paper studies a remanufacturing MC supply chain, in which the manufacturer produces and sells the new MC products with modular design *via* its brand retailer, and meanwhile the manufacturer or the retailer also remanufactures the used MC products. We develop three remanufacturing modes: the centralized supply chain, the manufacturer-remanufacturing mode, and the retailer-remanufacturing mode. We examine the optimal modularity level of new MC products and the best remanufacturing mode of used MC products. The special impact of modularity level on remanufacturing MC supply chain is also explored. Findings show that the manufacturer-remanufacturing mode can

Table 5. Insights and managerial implications.

Mian insights	Managerial implications
Remanufacturer choice for MC supply chain	(i) A low modularity-related production cost drives MC supply chain to choose manufacturer as the remanufacturer for an all-win situation. (ii) For selling more remanufactured MC products, MC supply chain should prioritize retailer as the remanufacturer.
Modularity level setting for manufacturer	(i) As the modularity-related production cost or consumer valuation of remanufactured MC products increases, the manufacturer should increase the modularity level in manufacturer-remanufacturing mode but decrease it in retailer-remanufacturing mode
Modular design collaboration suggestion for retailer	(i) To be able to gain more marginal profits from higher retail price without compromising consumer welfare, the retailer should cooperate with the manufacturer to design MC products with the aim of increasing the module level.
Purchasing channel choice for consumers	(i) For a higher customization level, consumers should purchase from manufacturing-remanufacturing channel; for a lower retail price, consumers should purchase from retailer-remanufacturing channel. (ii) For a higher consumer welfare, if the modularity-related production cost is low, consumers ought to purchase from manufacturing-remanufacturing channel; otherwise, consumers ought to purchase from retailer-remanufacturing channel.

achieve a win-win-win situation for manufacturer, retailer, and consumers, whereas retailer-remanufacturing mode cannot achieve such a situation. We surprisingly find that, however, retailer-remanufacturing mode (*i.e.*, a decentralized system) can generate a higher demand for remanufactured MC products, compared to the fully coordinated, centralized supply chain without double marginal effect. The main managerial insights about remanufacturing MC supply chain are summarized in Table 5.

This paper exists several limitations, which provides fruitful directions for future research. First, this paper only considers the customized products. However, in many industries such as computer and apparel, the supply chain produces and sells both standard and customized products together [41]. Thus, it is more realistic to investigate the new-product modular design along with the used-product remanufacturing, under the scenario that the supply chain offers both standard and customized products. Second, this paper focuses on studying the performance of the manufacturer or the retailer on remanufacturing the used MC products. In future research, it is important to investigate this question from the perspective of whole supply chain [38, 50, 52], and design a suitable contract for supply chain members to coordinate the remanufacturing MC supply chain and then improve supply chain performance [10,12]. Third, we consider a remanufacturing MC supply chain with sufficient capital. However, due to huge operation cost caused by MC implementation [9] and remanufacturing production [29], the combination of MC and remanufacturing can easily result in a dilemma of insufficient capital. This reminds us in future research to explore the optimal financing strategy for a remanufacturing MC supply chain with capital constraints. Fourth, this paper only briefly considers the situation where both demand and yield are certain. However, the random demand for MC products [6] and the uncertain yield of remanufactured products [28] may make the remanufacturing MC supply chain more complex but more realistic, which inspires us in future to examine a remanufacturing MC supply chain under yield and demand uncertainty. Fifth, we do not consider the remanufacturing authorization of used MC products in this paper. The remanufacturing authorization can be used as an effective way to alleviate OEMs from being encroached by the third-party remanufacturers in practice [57, 58]. Hence, we can further explore the remanufacturing authorization strategy for a MC supply chain.

Appendix A.

To ensure the concavity of profit function and the non-negativity of equilibrium solutions, the following inequality assumption is necessary: $(1-\delta)c < v < \min\{1-\delta, \delta + c\}$. Since the logic of deriving equilibrium solutions is similar in proposed models, we outline it explicitly for Model M only, as shown in follows.

The Hessian matrix of π_r^M can be given as follows:

$$H = \begin{bmatrix} \frac{\partial^2 \pi_r^M}{\partial p_n^2} & \frac{\partial^2 \pi_r^M}{\partial p_n \partial p_r} \\ \frac{\partial^2 \pi_r^M}{\partial p_r \partial p_n} & \frac{\partial^2 \pi_r^M}{\partial p_r^2} \end{bmatrix} = \begin{bmatrix} \frac{-2}{(1-\delta)m} & \frac{2}{(1-\delta)m} \\ \frac{2}{(1-\delta)m} & \frac{-2}{\delta(1-\delta)m} \end{bmatrix}.$$

The determinants of all principal submatrices for H are $H_1 = -\frac{2}{m(1-\delta)} < 0$ and $H_2 = \frac{4}{\delta(1-\delta)m^2} > 0$. Thus, π_r^M is jointly concave in p_n and p_r. By solving the equations $\frac{\partial \pi_r^M}{\partial p_n} = \frac{\partial \pi_r^M}{\partial p_r} = 0$, we can obtain the retailer's best response functions, *i.e.*, $p_n^{MRU} = \frac{m+w_n}{2}$ and $p_r^{MRU} = \frac{\delta m + w_r}{2}$. Substituting the best response functions into π_m^M, the $\pi_m^M(m, w_n, w_r) = \frac{-\delta(1-\delta)(km+c)m^2 + ((1-\delta)(\delta w_n + c w_r) + v(\delta w_n - w_r))m + 2\delta w_n w_r - \delta w_n^2 - w_r^2}{2\delta(1-\delta)m}$ can be obtained. Then, the Hessian matrix of $\pi_m^M(m, w_n, w_r)$ can be given as follows:

$$H = \begin{bmatrix} \frac{\partial^2 \pi_m^M(m,w_n,w_r)}{\partial {w_n}^2} & \frac{\partial^2 \pi_m^M(m,w_n,w_r)}{\partial w_n \partial w_r} & \frac{\partial^2 \pi_m^M(m,w_n,w_r)}{\partial w_n \partial m} \\ \frac{\partial^2 \pi_m^M(m,w_n,w_r)}{\partial w_r \partial w_n} & \frac{\partial^2 \pi_m^M(m,w_n,w_r)}{\partial {w_r}^2} & \frac{\partial^2 \pi_m^M(m,w_n,w_r)}{\partial w_r \partial m} \\ \frac{\partial^2 \pi_m^M(m,w_n,w_r)}{\partial m \partial w_n} & \frac{\partial^2 \pi_m^M(m,w_n,w_r)}{\partial m \partial w_r} & \frac{\partial^2 \pi_m^M(m,w_n,w_r)}{\partial m^2} \end{bmatrix}$$

$$= \begin{bmatrix} \frac{-1}{(1-\delta)m} & \frac{1}{(1-\delta)m} & \frac{w_n - w_r}{(1-\delta)m^2} \\ \frac{1}{(1-\delta)m} & \frac{-1}{\delta(1-\delta)m} & \frac{w_r - \delta w_n}{\delta(1-\delta)m^2} \\ \frac{w_n - w_r}{(1-\delta)m^2} & \frac{w_r - \delta w_n}{\delta(1-\delta)m^2} & \frac{\delta^2 k m^3 - \delta\left(k m^3 + w_n^2 - 2 w_n w_r\right) - w_r^2}{\delta(1-\delta)m^3} \end{bmatrix}.$$

Since the determinants of all principal submatrices for above Hessian matrix are $H_1 = -\frac{1}{(1-\delta)m} < 0$, $H_2 = \frac{1}{\delta(1-\delta)m^2} > 0$, and $H_3 = -\frac{k}{\delta(1-\delta)m^2} < 0$, $\pi_m^M(m, w_n, w_r)$ is jointly concave in m, w_n, and w_r. Solving the equations $\frac{\partial \pi_m^M(m,w_n,w_r)}{\partial m} = \frac{\partial \pi_m^M(m,w_n,w_r)}{\partial w_n} = \frac{\partial \pi_m^M(m,w_n,w_r)}{\partial w_r} = 0$, we can obtain m^{M*}, w_n^{M*}, and w_r^{M*}. Then, p_n^{M*} and p_r^{M*} can be obtained by substituting m^{M*}, w_n^{M*}, and w_r^{M*} into p_n^{MRU} and p_r^{MRU}. Similarly, the equilibrium solutions of Model C and Model R can be obtained, which are summarized in Table 2.

Proof of Lemma 4.1. $m^{C*} = 2m^{M*}$, $m^{M*} - m^{R*} = \frac{(\delta+v-c)^2}{8\delta k} > 0$. □

Proof of Lemma 4.2. $p_n^{C*} - p_n^{M*} = \frac{(1+3c)m^{C*}}{8} > 0$. $p_n^{M*} > p_n^{R*}$ since $p_n^{M*} = \frac{(3+c)m^{M*}}{4}$, $p_n^{R*} = \frac{(3+2c-\delta-v)m^{R*}}{4}$, $\frac{3+c}{4} - \frac{3+2c-\delta-v}{4} = \frac{v+\delta-c}{4} > 0$, and $m^{M*} > m^{R*}$. $q_n^{C*} = 2q_n^{M*} = 2q_n^{R*}$. □

Proof of Lemma 4.3. $p_r^{C*} - p_r^{M*} = \frac{(\delta+3c-3v)m^{C*}}{8} > 0$ if $v < \frac{\delta+3c}{3}$. $p_r^{C*} > p_r^{R*}$ since $p_r^{C*} = \frac{(\delta+c-v)m^{C*}}{2}$, $p_r^{R*} = \frac{(\delta+c-v)m^{R*}}{2}$, and $m^{C*} > m^{R*}$. $p_r^{M*} > p_r^{R*}$ since $p_r^{M*} = \frac{(3\delta+c-v)m^{M*}}{4}$, $p_r^{R*} = \frac{(\delta+c-v)m^{R*}}{2}$, $\frac{3\delta+c-v}{4} - \frac{\delta+c-v}{2} = \frac{\delta+v-c}{4} > 0$, and $m^{M*} > m^{R*}$. $q_r^{C*} = 2q_r^{M*}$. $q_r^{R*} - q_r^{C*} = \frac{1-\delta-v}{4(1-\delta)} > 0$. □

Proof of Corollary 4.4. The models under exogenous m are the same as those under endogenous, except that m is fixed rather than a decision variable. By backward induction method, the equilibrium solutions under exogenous m can be derived as follows: $w_n^{M*} = \frac{(1+c)m}{2}$, $w_n^{R*} = \frac{(1+2c-\delta-v)m}{2}$, $w_r^{M*} = \frac{(\delta+c-v)m}{2}$, $p_n^{C*} = \frac{(1+c)m}{2}$, $p_n^{M*} = \frac{(3+c)m}{4}$, $p_n^{R*} = \frac{(3+2c-\delta-v)m}{4}$, $p_r^{M*} = \frac{(3\delta+c-v)m}{4}$, $p_r^{C*} = p_r^{R*} = \frac{(\delta+c-v)m}{2}$, $CS^{C*} = 4CS^{M*} = \frac{Zm}{8\delta(1-\delta)}$, $CS^{R*} = \frac{Ym}{32\delta(1-\delta)}$, where $Y = (1-\delta)\left(\delta\left(1-v-c\right) + \left(3\delta + 4v - 4c\right)\left(\delta + v - c\right)\right) + \delta v^2$ and $Z = (1-\delta)\left(\delta + c^2 - 2\delta c - 2cv\right) + v^2$.

$\frac{\partial w_n^{R*}}{\partial m} = \frac{1+2c-\delta-v}{2} > 0$. $\frac{\partial w_n^{M*}}{\partial m} - \frac{\partial w_n^{R*}}{\partial m} = \frac{\delta+v-c}{2} > 0$. $\frac{\partial w_r^{M*}}{\partial m} = \frac{\delta+c-v}{2} > 0$.

$\frac{\partial p_n^{C*}}{\partial m} = \frac{1+c}{2} > 0$. $\frac{\partial p_n^{R*}}{\partial m} - \frac{\partial p_n^{C*}}{\partial m} = \frac{1-\delta-v}{4} > 0$. $\frac{\partial p_n^{M*}}{\partial m} - \frac{\partial p_n^{R*}}{\partial m} = \frac{\delta+v-c}{4} > 0$.
$\frac{\partial p_r^{C*}}{\partial m} = \frac{\partial p_r^{R*}}{\partial m} = \frac{\delta+c-v}{2} > 0$. $\frac{\partial p_r^{M*}}{\partial m} - \frac{\partial p_r^{C*}}{\partial m} = \frac{\delta+v-c}{4} > 0$. □

Proof of Lemma 4.5. $\pi_m^{M*} > \pi_m^{R*}$ since $\pi_m^{M*} = \frac{k}{2}\left(m^{M*}\right)^2$, $\pi_m^{R*} = \frac{k}{2}\left(m^{R*}\right)^2$, and $m^{M*} > m^{R*}$. $\pi_r^{R*} - \pi_r^{M*} = \frac{(\delta+v-c)^2 F_1(c)}{128k\delta^2(1-\delta)}$, where $F_1(c) = -(1-\delta)c^2 + 2(1-\delta)(\delta+v)c + 3\delta^3 + (6v-5)\delta^2 + \left(3v^2-6v+2\right)\delta - v^2$. Thus, the positivity or negativity of $\pi_r^{R*} - \pi_r^{M*}$ is consistent with that of $F_1(c)$. Solving the equation $F_1(c) = 0$ with respect to c, we can obtain $c = \frac{(1-\delta)(\delta+v) \pm \sqrt{2\delta(1-\delta)(1-\delta-v)^2}}{1-\delta}$. Because $F_1(c)$ is symmetric about $\delta+v$, and $c < \delta+v$, the sole root of equation $F_1(c) = 0$ is $c_1(v,\delta) = \frac{(1-\delta)(\delta+v) - \sqrt{2\delta(1-\delta)(1-\delta-v)^2}}{1-\delta}$. Hence, if $c > c_1(v,\delta)$, then $\pi_r^{R*} > \pi_r^{M*}$; otherwise, $\pi_r^{R*} < \pi_r^{M*}$. □

Proof of Lemma 4.6. $\pi_t^{C*} = 2\pi_t^{M*}$. $\pi_t^{M*} - \pi_t^{R*} = \frac{(\delta+v-c)^4}{64k\delta^2} > 0$. $CS^{C*} = 8CS^{M*}$. $CS^{R*} - CS^{M*} = \frac{1}{2}\left(\pi_r^{R*} - \pi_r^{M*}\right)$, which is consistent with the proof of Lemma 4.5. □

Proof of Corollary 4.7. $\frac{\partial CS^{M*}}{\partial m} = \frac{(1-\delta)\left(\delta+c^2-2\delta c-2cv\right)+v^2}{32\delta(1-\delta)} > 0$. $\frac{\partial CS^{C*}}{\partial m} - \frac{\partial CS^{R*}}{\partial m} = \frac{3(1-\delta-v)^2}{32(1-\delta)} > 0$. $\frac{\partial CS^{R*}}{\partial m} - \frac{\partial CS^{M*}}{\partial m} = \frac{3(\delta+v-c)^2}{32\delta} > 0$. □

Proof of Extension 6.1. Since the logic of deriving equilibrium solutions is similar for Model BM and Model BR, we outline it explicitly for Model BM only, as shown in follows.

Solving the equations $\frac{\partial \pi_r^{BM}}{\partial p_n} = \frac{\partial \pi_r^{BM}}{\partial p_r} = 0$, we can obtain the retailer's best response functions, *i.e.*, $p_n^{BMR} = \frac{m+w_n}{2}$ and $p_r^{BMR} = \frac{\delta m+w_r}{2}$. Thus, the necessary optimality condition for $q_r \leq q_n$ is $w_n \leq \frac{\delta m(1-\delta)+(1+\delta)w_r}{2\delta}$. Substituting the best response functions into π_m^{BM}, we can obtain π_m^{BMR}. The manufacturer's Lagrangian function can be formulated as follows. $L_M = \pi_m^{BMR} - \lambda^M(w_n - \frac{\delta m(1-\delta)+(1+\delta)w_r}{2\delta})$, where $\lambda^M \geq 0$.

If $\lambda^M > 0$ (full remanufacturing). Solving equations $\frac{\partial L_M}{\partial m} = \frac{\partial L_M}{\partial w_n} = \frac{\partial L_M}{\partial w_r} = \frac{\partial L_M}{\partial \lambda^M} = 0$, we can obtain $m^{BMF*} = \frac{(1-2c+v+\delta)^2}{8k(1+3\delta)}$, $w_n^{BMF*} = \frac{(2(1+3\delta)-(1+\delta)(1-2c+v+\delta))m^{BMF*}}{2(1+3\delta)}$, $w_r^{BMF*} = \frac{\delta(2c+2\delta-v)m^{BMF*}}{1+3\delta}$, and $\lambda^{M*} = \frac{(1+\delta)v-(1-\delta)(\delta+c)}{(1+3\delta)(1-\delta)}$. Thus, $p_n^{BMF*} = \frac{\left((2c-v)(1+\delta)-\delta^2+10\delta+3\right)m^{BMF*}}{4(1+3\delta)}$, $p_r^{BMF*} = \frac{\delta(1-v+2c+5\delta)m^{BMF*}}{2(1+3\delta)}$, $q_n^{BMF*} = q_r^{BMF*} = \frac{1-2c+v+\delta}{4(1+3\delta)}$, and $\pi_m^{BMF*} = \pi_r^{BMF*} = 2CS^{BMF*} = \frac{k\left(m^{BMF*}\right)^2}{2}$.

If $\lambda^M = 0$ (partial remanufacturing). Solving the equations $\frac{\partial L_M}{\partial m} = \frac{\partial L_M}{\partial w_n} = \frac{\partial L_M}{\partial w_r} = \lambda^M = 0$, we can obtain that $m^{BMP*} = \frac{(1-\delta)\left(\delta+c^2-2\delta c-2cv\right)+v^2}{8\delta k(1-\delta)}$, $w_n^{BMP*} = \frac{(1+c)m^{BMP*}}{2}$, $w_r^{BMP*} = \frac{(\delta+c-v)m^{BMP*}}{2}$. Then, $p_n^{BMP*} = \frac{(3+c)m^{BMP*}}{4}$, $p_r^{BMP*} = \frac{(3\delta+c-v)m^{BMP*}}{4}$, $q_n^{BMP*} = \frac{1-\delta-v}{4(1-\delta)}$, $q_r^{BMP*} = \frac{v-(1-\delta)c}{4\delta(1-\delta)}$, and $\pi_m^{BMP*} = \pi_r^{BMP*} = 2CS^{BMP*} = \frac{k\left(m^{BMP*}\right)^2}{2}$.

From $\lambda^{M*} = \frac{(1+\delta)v-(1-\delta)(\delta+c)}{(1+3\delta)(1-\delta)}$, we find that only if $v > v^{M*} = \frac{(1-\delta)(\delta+c)}{1+\delta}$, then $\lambda^{M*} > 0$ in which the full remanufacturing is chosen since $q_r^* = q_n^*$ in this case; if $v < v^{M*}$, then $\lambda^{M*} = 0$ in which the partial remanufacturing is chosen since $q_r^* < q_n^*$ in this case.

Thus, Proposition 6.1 can be easily obtained.

Similarly, we can obtain the equilibrium solutions of Model BR as follows.

When $v > v^{R*} = (1-\delta)c$ in which the full remanufacturing is chosen,

$m^{BRF*} = \frac{(\delta+v-c)((1-\delta)(\delta+c)-(1+\delta)v)}{8k\delta^2}$, $w_n^{BRF*} = \frac{(\delta(1-\delta)+(1+\delta)(c-v))m^{BRF*}}{2\delta}$, $p_n^{BRF*} = \frac{(\delta(3-\delta)+(1+\delta)(c-v))m^{BRF*}}{4\delta}$, $p_r^{BRF*} = \frac{(c+\delta-v)m^{BRF*}}{2}$, $q_n^{BRF*} = q_r^{BRF*} = \frac{\delta+v-c}{4\delta}$, $\pi_m^{BRF*} = \frac{k\left(m^{BRF*}\right)^2}{2}$, $\pi_r^{BRF*} = \frac{(\delta+v-c)^2(1+3\delta)m^{BRF*}}{16\delta^2}$, and $CS^{BRF*} = \frac{(\delta+v-c)^2(1+3\delta)m^{BRF*}}{32\delta^2}$.

When $v < v^{R*} = (1-\delta)c$ in which the full remanufacturing is chosen,

$m^{BRP*} = \frac{(1-\delta-v)^2}{8k(1-\delta)}$, $w_n^{BRP*} = \frac{(1+2c-\delta-v)m^{BRP*}}{2}$, $p_n^{BRP*} = \frac{(3+2c-\delta-v)m^{BRP*}}{4}$, $p_r^{BRP*} = \frac{(c+\delta-v)m^{BRP*}}{2}$, $q_n^{BRP*} = \frac{1-\delta-v}{4(1-\delta)}$, $q_r^{BRP*} = \frac{(1-\delta)(\delta-2c)+v(2-\delta)}{4\delta(1-\delta)}$, $\pi_m^{BRF*} = \frac{k\left(m^{BRP*}\right)^2}{2}$, $\pi_r^{BRF*} = \frac{(1-\delta-v)^2 Y}{128k\delta(1-\delta)^2}$, and $CS^{BRF*} = \frac{(1-\delta-v)^2 Y}{256k\delta(1-\delta)^2}$, where $Y = (1-\delta)\left(\delta\left(1-v-c\right) + \left(3\delta+4v-4c\right)\left(\delta+v-c\right)\right) + \delta v^2$.

Based on above equilibrium solutions, we can obtain that,

(i) $v < (1-\delta)c$, $m^{BM*} - m^{BR*} = m^{BMP*} - m^{BRP*} = \frac{(\delta+v-c)^2}{8\delta k} > 0$;

(ii) $(1-\delta)c < v < \frac{(1-\delta)(\delta+c)}{1+\delta}$,

$m^{BM*} - m^{BR*} = m^{BMP*} - m^{BRF*} = \frac{\left(1-\delta^2+\delta\right)v^2 + 2(1-\delta)\left(\delta^2-(1+\delta)c\right)v + (1-\delta)\left(\delta^3-2\delta^2 c+c^2\right)}{8\delta^2(1-\delta)k}$

$\geq \frac{\left(1-\delta^2+\delta\right)((1-\delta)c)^2 + 2(1-\delta)\left(\delta^2-(1+\delta)c\right)(1-\delta)c + (1-\delta)\left(\delta^3-2\delta^2 c+c^2\right)}{8\delta^2(1-\delta)k} = \frac{\delta(1-c)^2}{8k} > 0$;

(iii) $\frac{(1-\delta)(\delta+c)}{1+\delta} < v$, $m^{BM*} - m^{BR*} = m^{BMF*} - m^{BRF*} = \frac{\left(-2\delta^2+(c-2v)\delta+c-v\right)^2}{8\delta^2(1+3\delta)k} > 0$.

Then, Proposition 6.2 can be derived. □

Proof of Extension 6.2. Since the logic of deriving equilibrium solutions is similar for both models, we outline it explicitly for Model LM only, as shown in follows.

Let $z_n = p_n - w_n$ and $z_r = p_r - w_r$ represent the marginal profits from selling new and remanufactured MC products, respectively. Then, the MC manufacturer's profit function can be rewritten as follows: $\pi_m^{LM} = (w_n - cm)\left(1 - (z_n + w_n) + \beta\left(z_r + w_r\right) + m\right) - \frac{km^2}{2} + \left(w_r - (cm - vm)\right)\left(1 - (z_r + w_r) + \beta\left(z_n + w_n\right) + m\right)$.

Similar to Model M, π_m^{LM} is strictly a concave function, with the only maximum value of m, w_n, and w_r. The first-order condition of π_m^{LM} are as follows:

$\frac{\partial \pi_m^{LM}}{\partial m} = \left(\left(w_n + w_r + z_n + z_r\right)(1-\beta) - 2\left(1+2m\right)\right)c - km + w_n + w_r + \left(2m + \beta\left(z_n + w_n\right) - w_r - z_r + 1\right)v = \left(\left(p_n + p_r\right)(1-\beta) - 2\left(1+2m\right)\right)c - km + w_n + w_r + \left(2m + \beta p_n - p_r + 1\right)v$,

$\frac{\partial \pi_m^{LM}}{\partial w_n} = \left(\left(v-c\right)m + 2w_r + z_r\right)\beta + (1+c)m - 2w_n - z_n + 1 = \left(\left(v-c\right)m + w_r + p_r\right)\beta + (1+c)m - w_n - p_n + 1$,

$\frac{\partial \pi_m^{LM}}{\partial w_r} = \left(2w_n + z_n\right)\beta + \left(1 - v + (1-\beta)c\right)m - 2w_r - z_r + 1 = \left(w_n + p_n\right)\beta + \left(1 - v + (1-\beta)c\right)m - w_r - p_r + 1$.

Solving the equations $\frac{\partial \pi_m^{LM}}{\partial m} = \frac{\partial \pi_m^{LM}}{\partial w_n} = \frac{\partial \pi_m^{LM}}{\partial w_r} = 0$, we obtain the manufacturer's best response functions for the given retail prices, which are shown follows:

$m^{LMB} = \frac{((1-c)(1-\beta)+\beta(c(1-\beta)-v))(p_n+p_r)-(1-\beta)(v-2c)+v\left(\beta^2 p_n+p_r\right)-2}{(v-2c-k)(1-\beta)+2}$,

$w_n^{LMB} = \frac{\left(2(1-\beta)(c+p_n)+(\beta(1+\beta p_n)+p_r-1)v-\left((1-\beta)^2 c+\beta v\right)(p_n+p_r)-2\right)c+((1-\beta)p_n-1)k+(1+v)(p_r-p_n)}{(v-2c-k)(1-\beta)+2}$,

$w_r^{LMB} = \frac{X_{LMB}}{(v-2c-k)(1-\beta)+2}$, where $X_{LMB} = ((\beta(2v-3c) - \beta^2 c - c)(p_n + p_r) + ((2p_n + p_r)\beta^2 - 3(1-\beta) + p_n + 2p_r)v + 2((1-\beta)(c+p_r) - 1))c + (\beta v^2 - v)(p_n + p_r) + (1 - \beta - \beta^2 p_n - p_r)v^2 + 2v(1 + \beta p_r) + ((1-\beta)p_r - 1)k + p_n - p_r$.

Substituting above best response functions into retailer's profit function, we can obtain π_r^{LMB}. By the equations $\frac{\partial \pi_r^{LMB}}{\partial p_n} = \frac{\partial \pi_r^{LMB}}{\partial p_r} = 0$, the optimal retail prices for new and remanufactured MC products in Model LM can derived as follows:

$p_n^{LM*} = \frac{(1-\beta)(7(1-\beta)c-3v-5)v+2(1-\beta)\left(6c+3k-4(1-\beta)c^2\right)-4}{4(1-\beta)((1-\beta)(2c(1-\beta)(v-c)+2(2c+k)-v(2+v))-2)}$,

$p_r^{LM*} = \frac{(1-\beta)(9(1-\beta)c-(4-\beta)v-7)v+2(1-\beta)\left(6c+3k-4(1-\beta)c^2\right)-4}{4(1-\beta)((1-\beta)(2c(1-\beta)(v-c)+2(2c+k)-v(2+v))-2)}$.

Substituting p_n^{LM*} and p_r^{LM*} into the manufacturer's best response functions (*i.e.*, m^{LMB}, w_n^{LMB}, and w_r^{LMB}), the equilibrium modularity level, wholesale prices of new and remanufactured MC products are obtained, denoted as m^{LM*}, w_n^{LM*}, and w_r^{LM*}. Then, other equilibrium solutions of Model LM can be obtained as follows.

$q_n^{LM*} = 1 - p_n^{LM*} + \beta p_r^{LM*} + m^{LM*}$, $q_r^{LM*} = 1 - p_r^{LM*} + \beta p_n^{LM*} + m^{LM*}$,

$\pi_m^{LM*} = \left(w_n^{LM*} - cm^{LM*}\right)q_n^{LM*} + \left(w_r^{LM*} - \left(cm^{LM*} - vm^{LM*}\right)\right)q_r^{LM*} - \frac{k}{2}\left(m^{LM*}\right)^2$,

$\pi_r^{LM*} = \left(p_n^{LM*} - w_n^{LM*}\right)q_n^{LM*} + \left(p_r^{LM*} - w_r^{LM*}\right)q_r^{LM*}$, $\pi_t^{LM*} = \pi_r^{LM*} + \pi_m^{LM*}$, $CS^{LM*} = \frac{\left(q_n^{LM*}\right)^2 + \left(q_r^{LM*}\right)^2}{2}$.

Similarly, we can obtain the equilibrium solutions of Model LR, as shown in follows.

$p_n^{LR*} = \frac{X_{LRn}}{Y_{LR}}$, where $X_{LRn} = (1-\beta^2)c^4+(2(1+v)\beta^2-\beta-2v-3)c^3+(3+v^2+5k+5v-(1+v^2+4v)\beta^2+(2-5k+v)\beta)c^2+(2v(1+v)\beta^2+((3k-2)v+5k-1)\beta-2v^2-(4+k)v-8k-1)c-\beta^2v^2+((1-3k)v+2k^2)\beta-(2k-v-1)(3k+v)$, $Y_{LR} = ((2v^2+(6-4k)v-4k+2)\beta^2-2v(1+v)\beta^3+2(v^2+(2k+1)v+6k-1)\beta-2v^2-8k-6v-4)c+\beta^3v^2-(v^2-(4k-2)v)\beta^2+(8k^2-4kv-v^2-4k+1)\beta-8k^2+v^2+4k+2v+1+((1+v^2+4v)\beta^3+(4k-v^2-6v-5)\beta^2-(8k+4v+v^2)\beta+v^2+4k+6v+6)c^2+(1+\beta)(1-\beta)^2c^4-2(1-\beta)(2+v-(1+v)\beta)(1+\beta)c^3$.

$p_r^{LR*} = \frac{X_{LRr}}{Y_{LR}}$, where $X_{LRr} = (1-\beta^2)c^4+(2(1+v)\beta^2-\beta-2v-3)c^3+(3+v^2+3k+5v-(1+v^2+4v)\beta^2+(2-3k+v)\beta)c^2+(2v(1+v)\beta^2+((3k-2)v+3k-1)\beta-2v^2-(4+k)v-4k-1)c-\beta^2v^2+(1-3k)v\beta+v^2+(1+k)v-4k^2+k$.

$m^{LR*} = \frac{(1-c)\left(1+\beta p_r^{LR*}-p_n^{LR*}\right)}{c+k-1}$, $w_n^{LR*} = \frac{\left(c-c^2+k\right)\left(1+\beta p_r^{LR*}-p_n^{LR*}\right)}{c+k-1}$, $q_n^{LR*} = 1-p_n^{LR*}+\beta p_r^{LR*}+m^{LR*}$,

$q_r^{LR*} = 1-p_r^{LR*}+\beta p_n^{LR*}+m^{LR*}$, $\pi_r^{LR*} = \left(p_n^{LR*}-w_n^{LR*}\right)q_n^{LR*}+\left(p_r^{LR*}-\left(cm^{LR*}-vm^{LR*}\right)\right)q_r^{LR*}$,

$\pi_m^{LR*} = \left(w_n^{LR*}-cm^{LR*}\right)q_n^{LR*}-\frac{k}{2}\left(m^{LR*}\right)^2$, $\pi_t^{LR*} = \pi_r^{LR*}+\pi_m^{LR*}$, $CS^{LR*} = \frac{\left(q_n^{LR*}\right)^2+\left(q_r^{LR*}\right)^2}{2}$. □

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