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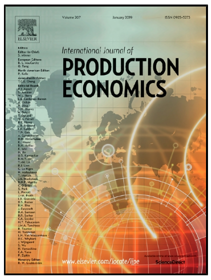


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# Cooperative Game Approaches to Coordinating a Three-echelon Closed-loop Supply Chain with Fairness Concerns

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**Abstract:** This paper investigates a three-echelon closed-loop supply chain (CLSC) consisting of a manufacturer, a distributor, and a retailer, where the retailer exhibits fairness concerns. Cooperative and non-cooperative game theoretic analyses are employed to characterize interactions among different parties. Analytical results confirm the conventional wisdom: with the retailer's fairness concerns, the channel profits under the decentralized and partial-coalition models underperform that under the centralized model. To find an appropriate profit allocation scheme to coordinate the supply chain system with fairness concerns, we resort to the cooperative game theory. To this end, we first derive the characteristic function form of the cooperative game based on the equilibrium profits under centralized, decentralized and different partial-coalition models. Subsequently, we propose three coordination mechanisms based on the Shapley value, nucleolus solution, and equal satisfaction to allocate surplus profit. The three mechanisms are then evaluated by using numerical experiments. We further examine how the retailer's fairness concerns affect profit allocation under the three mechanisms. The key innovation is to incorporate the retailer's fairness concerns into the coordination of a three-echelon CLSC. Our contributions are twofold: First, cooperative game-theoretic mechanisms are put forward to coordinate the three-echelon CLSC with a fairness-minded retailer. Second, we investigate how the retailer's fairness concerns affect the CLSC members' pricing decision and surplus profit allocation. Our studies confirm that the resulting profit allocation schemes satisfy both individual and collective rationality and fall in the core of the cooperative game, thereby making the grand coalition stable and suggesting viable options to coordinate the CLSC system. Further analyses reveal that different coordination mechanisms benefit the three CLSC members differently. These research findings help CLSC managers to understand what options are available and identify possible pathways for them to foster cooperation and achieve equitable allocation of surplus profit.

**Keywords:** Closed-loop supply chain; Cooperative game; Fairness concerns; Coordination; Profit allocation.

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# Cooperative Game Approaches to Coordinating a Three-echelon Closed-loop Supply Chain with Fairness Concerns

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## 1. Introduction

Increasing environmental pressure, stricter legislation, and competitive business environment have led more and more firms to engage in remanufacturing and recycling used products, resulting in closed-loop supply chains (CLSCs). A popular trend in CLSC management is that the members join coalitions and pool their critical resources to enhance their power in the supply chain (Jena and Sarmah, 2014; Leng and Parlar, 2009; Nagarajan and Sošić, 2008; Zhang and Liu, 2013). For example, it has been recognized that forging partnerships is key for automakers to succeed in recycling and remanufacturing auto parts in end-of-use automobiles (IRIS, 2010). In Europe, Tesla works with Umicore to recycle and recover electric vehicle batteries and resell them to battery manufacturers. This is not only an attractive recycling mechanism from an environmental perspective, but it also provides a substantial source of revenue (Gu et al., 2018). For distributors, they are closer to customers and have a better understanding of market conditions. As such, they tend to be more receptive to remanufacturing and are willing to take more responsibility in collaborating with manufacturers (Li et al., 2011). In CLSCs, distributors often partner with manufacturers in collecting used products (Jena and Sarmah, 2014). For instance, as a distributor of a Japanese general machinery maker, Komatsu Ltd., Nanjing Gangjia Komatsu Construction Machinery Limited not only sells new products but also cooperates with Komatsu in renewing and reselling used products in Jiangsu and Xinjiang, China (Xiong and Wang, 2011). Similarly, Lei Shing Hong Machinery, the distributor of Caterpillar Machinery in Shanghai and Jiangsu, works with Caterpillar in remanufacturing old equipment and reselling it to the marketplace (Xiong and Wang, 2011). By forming strategic alliances and sharing information with other members in a CLSC, a firm can enhance both individual and channel profitability. Therefore, it has become a critical issue to understand how to foster cooperation in a CLSC (Chen et al., 2017b).

Under a cooperative framework, how can supply chain members navigate through the competitive environment and be incentivized to remain committed to cooperation? An equitable profit allocation scheme serves as a viable solution. To address this issue, researchers have proposed many contracting forms, such as quantity discount, buy-back, two-part tariff, revenue-sharing contracts and mail-in rebate (Govindan and Popiuc, 2014; Noori-daryan et al., 2018; Saha et al., 2016; Taleizadeh et al., 2016; Taleizadeh et al., 2018b). Another line of thinking is to resort to the cooperative game theory as it examines all possible coalition outcomes and what players can achieve individually as well as through forming coalitions. In addition, it also addresses the stability and robustness of different coalitions and how surplus is allocated among coalition members (Nagarajan and Sošić, 2008). The first step in applying the cooperative game theory is to identify the set of all possible coalition outcomes and characterize its properties, thereby determining how players ultimately gain from different outcomes in this set. Existing applications of cooperative game models tend to address the allocation issue by employing any arbitrary coalition structure and assuming equal power among members (Granot and Sošić, 2003; Guajardo and Rönnqvist, 2016; Guardiola et al., 2009; Meca et al., 2004). This treatment makes it easy to identify the set of all possible coalition outcomes; however, a CLSC is featured with a more complex coalition structure where certain horizontal and vertical coalitions cannot be formed due to different reasons such as unequal power status among members. To understand the coalition structure of a CLSC, we first consider it in a non-cooperative environment and examine the case where different players carry out CLSC operations based on their individual considerations. This noncooperative game model is subsequently employed to generate the set of all possible coalition outcomes, furnishing the basis for further analysis in the cooperative setting.

Non-cooperative game theoretic models have been extensively employed in CLSC management to delineate the competitive environment, characterize interaction among players, and analyze pricing strategies and their implications on profitability. At the micro level, these models are convenient tools for examining the bargaining power of different members and determining contracting parameters based on equilibriums in a CLSC (Nagarajan and Sošić, 2008). This equilibrium analysis is an important step that must be taken before cooperative game models can be entertained to address surplus profit allocation in a CLSC owing to cooperation between member firms.

To properly allocate the resulting surplus profit, the cooperative game theory provides many potential solutions. Among these alternatives, one-point solution concepts (Li, 2016) such as the Shapley value, the nucleolus solution, and the Equal Profit Method (EPM) are sensible choices as they each provide a unique allocation scheme if existent. The Shapley value is calculated by averaging a member's marginal contributions to all coalitions under all possible orderings (Bilbao and Edelman, 2000). The nucleolus solution is derived by lexicographically minimizing the largest degree of dissatisfaction (Arin and Feltkamp, 1997). The EPM aims to allocate profit to each participant as equally as possible and can be formulated as a linear program (Frisk et al., 2010). These three cooperative game approaches will be employed as the basis to allocate surplus profit as a result of cooperation among CLSC members in this research.

Generally, the aforementioned research assumes that the agents are completely rational. In reality, decision-makers often exhibit bounded rationality and demonstrate different social preferences such as fairness concerns. Although relatively limited studies incorporate noneconomic considerations into CLSCs, these behavioural factors do influence CLSC members' decisions and channel profit (Ma et al., 2017). In today's industrial practice, sustainable cooperation and fairness concerns widely coexist in CLSCs. For instance, Gree Inc., one of the world largest specialized air-conditioner manufacturer in China, establishes coalitions with different firms, such as Tianjian Recycling Development Co., Ltd and Shijiazhuang Green Recycling Co., Ltd, to assist them in remanufacturing and distributing its products (Gree, 2018). These firms are not only involved in Gree's import and export distribution business, but they also collect and remanufacture its used products. Gree and its supply chain partners coordinate their operations in many ways, and Gree often invests in their infrastructure construction such as collection and distribution networks. But supply chain relationships are not always harmonious. Gome, one of the largest household appliance retailers in China, decided to terminate its cooperation with Gree in March 2004 after its demand for higher-than-normal kickbacks was rejected by Gree. Gome, in this case, was concerned with distributional fairness and wanted to capitalize on its dominating power in the retailing industry to extract more profit from the manufacturer. (Chen and Wu, 2013; Liu et al., 2015). This case demonstrates that a focal firm in a CLSC (e.g., the manufacturer) has to pay close attention to the coordination mechanism so that sustainable cooperation can be achieved when some partners are fairness-minded. Existing literature suggests that the channel profit usually suffers when supply chain members negotiate profit-sharing in typical coordination contracts under noneconomic preferences such as risk aversion and fairness concerns (Nagarajan and Sošić, 2008; Nie and Du, 2017). It remains largely unaddressed regarding how to formulate proper profit allocation schemes to facilitate cooperation at maximal channel efficiency with fairness-minded players. We attempt to address this issue by resorting to the cooperative game theory.

More specifically, we incorporate the retailer's fairness concerns into a typical three-echelon CLSC consisting of a manufacturer (M), a distributor (D), and a retailer (R). Four scenarios are examined: (1) The centralized case where a central planner makes integrated decisions for the three members (CC); (2) The decentralized case where the three members make independent decisions (CD); (3) M and D form a coalition (MD); and (4) D forms a coalition with R (DR). This basic setting emphasizes D's irreplaceable role in the CLSC so that M and R cannot form a coalition without D. This research attempts to address the following three questions: (1) How to derive equilibrium pricing decisions, production quantities and profits for the CLSC with R's fairness concerns under the CC, CD, MD, and DR models based on the Stackelberg game setting? (2) How to allocate surplus profit by using cooperative game theoretic approaches? (3) What is the impact of R's fairness concerns on the performance of the three proposed coordination mechanisms?

The remainder of this paper is organized as follows. A brief review of literature is presented in Section 2. Section 3 describes the problem under consideration, followed by notation and assumptions in Section 4. Stackelberg equilibrium results are obtained for the centralized (CC), decentralized (CD), and two partial-coalition models (MD and DR) in Section 5. Three cooperative game theoretic mechanisms are then presented to coordinate the CLSC members in Section 6. Section 7 evaluates the performance of the three coordination mechanisms. Section 8 concludes the paper.

## 2. Literature review

In a multi-echelon CLSC, extensive game-theoretic analyses have been carried out from various perspectives, such as inventory systems (Hasanov et al., 2018), defective product returns (Taleizadeh and Noori-daryan, 2015; Taleizadeh et al., 2015), marketing effort (Zerang et al., 2018), product recycling uncertainties (Alamdar et al., 2018; Zhou et al., 2016), different channel power structures (Taleizadeh et al., 2017a), and channel selections (Taleizadeh et al., 2018a). Based on the research questions in this paper, we focus our review on the cooperation and coordination of three-echelon CLSCs, applications of cooperative game approaches to conventional supply chains and CLSCs, and coordination of supply chains with fairness concerns.

### 2.1. Cooperation and coordination of multi-party CLSCs

A critical issue in channel operations is cooperation and coordination of CLSCs, which has attracted considerable attention in academia and practice. Most of the existing studies are concerned with two-echelon CLSCs, and limited research has been carried out regarding three-echelon CLSCs (Govindan et al., 2013; Heydari et al., 2017; Xie et al., 2017). For instance, within a dual-recycling CLSC consisting of a manufacturer, a retailer, and a third-party collector, Taleizadeh et al. (2018a) develop an integrated two-tariff and cooperative advertising contract to coordinate the system and enhance each member's profit. In a fuzzy three-echelon CLSC setting, Alamdar et al. (2018) examine all possible alliance strategies and propose a new coordination mechanism that combines a fixed payment with a cost sharing component. In a CLSC with a manufacturer, a third-party remanufacturer, and a retailer, Zhang and Ren (2016) formulate a coordinated pricing mechanism that combines two-part tariff with a revenue-sharing contract to coordinate this supply chain. Saha et al. (2016) examine a CLSC comprising a manufacturer, a retailer, and a third-party collector and design a three-way discount mechanism to coordinate the channel and achieve a win-win situation for the three members. These studies show how different contract designs can coordinate the system and achieve a win-win profit allocation for all CLSC members, but they tend to ignore the impact of different coalition/cooperation structures on the members' bargaining powers in their negotiation for surplus profit allocation. To fill this gap in the literature, Ma et al. (2016) analyze the coalition formation process in a three-echelon CLSC consisting of a manufacturer, a retailer, and two recyclers. In the presence of a return policy, Taleizadeh et al. (2017b) perform a game-theoretic analysis on a joint pricing and alliance selection decision-making problem in a two-echelon retailer-led supply chain. Their focus is to compare profitability under various coalition structures. Li et al. (2017) investigate different coalition strategies under a three-echelon reverse supply chain setting where a collector, a remanufacturer, and two retailers may form various coalitions. This study identifies maximal economic and social benefit in a centralized model, but it does not address how to divide “this bigger pie”. The aforesaid research indicates that non-cooperative game models are well suited to deal with coalition formation in supply chains and identify what potential gains may exist, but it remains an unsettled issue as to how surplus profit in a centralized system should be properly allocated to foster cooperation among members.

**2.2. Applications of cooperative game approaches in supply chains**

An increasing number of researchers have been applying cooperative game theoretical models to supply chain management (Fiestras-Janeiro et al., 2011). This body of literature can take two different lines of thinking, either from a cost or a profit allocation angle.

The first stream of this literature addresses cost allocation in supply chains by using cooperative game theoretic models. For instance, Granot and Sošić (2003) study a decentralized supply chain system consisting of multiple retailers with stochastic demand. They examine the effect of different cost sharing rules among the retailers (e.g., Shapely value) on residual supply/demand. Leng and Parlar (2009) model a three-level supply chain where the characteristic function is obtained by computing the expected inventory cost of the three agents (i.e., a supplier, a manufacturer, and a retailer) in an information-sharing setting. After comparing different solution concepts in the cooperative game theory, they adopt the nucleolus solution to allocate inventory cost across the supply chain. These papers typically derive the characteristic function of cooperative game models by minimizing the total cost.

The second stream of existing research addresses profit allocation under different coalition structures in multi-echelon supply chains. To this end, Jena and Sarmah (2014) first examine the coalition formation and the related optimal profit in different non-cooperative and cooperative cases in a CLSC comprising two competitive manufacturers and a retailer. Then, they obtain the characteristic function based on equilibrium solutions in non-cooperative game models and develop a weighted Shapely value mechanism to distribute surplus profit in a fully coordinated model. Similarly, Zhang and Liu (2013) analyze coalition formation based on four non-cooperative models, thereby deriving the characteristic function for all coalitions and applying the Shapely value and asymmetric Nash negotiation to coordinate the supply chain system. It is worth noting that the Shapley value arises as the profit allocation scheme in the aforesaid two articles, but the resulting solution may not necessarily make the grand coalition stable (Leng and Parlar, 2009). This motivates us to consider other allocation methods on top of the Shapley value approach such as the nucleolus solution (Leng and Parlar, 2009; Noori-Daryan et al., 2017).

### 2.3. Supply chain coordination with fairness concerns

Another body of literature that is closely related to our research is channel coordination with fairness concerns. Along this line, Cui et al. (2007) incorporate fairness concerns into a dyadic supply chain comprising a manufacturer and a retailer and reveal that a simple wholesale price contract can coordinate such a channel when the retailer or both members are fairness-minded. By extending the linear demand function in Cui et al. (2007) to different nonlinear functions in the same supply chain setting, Caliskan-Demirag et al. (2010) perform a comparative analysis and find that an exponential demand function is easier to achieve coordination than the linear demand function. Yang et al. (2013) conceive cooperative advertising as a strategy to improve the performance of a supply chain consisting of one manufacturer and one retailer. Their study shows that cooperative advertising can coordinate the whole channel under certain conditions if only the retailer is fair-minded. Du et al. (2014) incorporate the newsvendor model into a dyadic supply chain where both the supplier and the retailer are fairness-minded. Their findings show that the traditional wholesale price contract can coordinate the fairness-minded channel based on affine transformation only if the scale factor falls within a small interval, implying that fairness concerns make it harder for channel coordination. Katok and Pavlov (2013) investigate the effect of three factors, fairness concerns, incomplete information, and propensity to make random errors, on the inefficiency of coordinating a simple supply chain with a supplier and a retailer. As for CLSCs, existing literature has investigated the impact of the retailer's fairness concerns on equilibrium decisions (Liu et al., 2017b; Ma et al., 2017). Liu et al. (2017b) further devise a revenue-sharing contract to coordinate a two-echelon CLSC with both members' fairness concerns. These studies reveal that fairness concerns make it more complicated to coordinate a supply chain and existing research along this line is generally confined to two-echelon supply chains within a non-cooperative game setting.

Based on the key features of our models, Table 1 frames our research in a proper literature context. The table reveals that the majority of extant literature concentrates on the coordination of supply chains in different two-echelon settings. Limited attention is dedicated to coordination by cooperative game approaches in multi-echelon CLSC settings. The focus of this paper differs from existing studies as it investigates the impact of R's fairness concerns on the coordination results in a three-echelon CLSC by employing three cooperative game approaches.

**Table 1.** Literature positioning of this research (Y=Yes; N=No)

| Reference | Closed-loop supply chain? | Multi-echelon supply chain? | Coalition structures? | Fairness concerns? | Cooperative game approaches? |
|---|---|---|---|---|---|
| Hasanov et al. (2018) | Y | Y | N | N | N |
| Taleizadeh et al. (2015) | Y | Y | N | N | N |
| Taleizadeh and Noori-daryan (2015) | Y | Y | N | N | N |
| Zerang et al. (2018) | Y | Y | N | N | N |
| Alamdar et al. (2018) | Y | Y | N | N | N |
| Zhou et al. (2016) | Y | Y | N | N | N |
| Taleizadeh et al. (2017a) | Y | Y | N | N | N |
| Taleizadeh et al. (2018a) | Y | Y | N | N | N |
| Heydari et al. (2017) | Y | N | N | N | N |
| Xie et al. (2017) | Y | N | N | N | N |
| Taleizadeh et al. (2018a) | Y | Y | N | N | N |
| Alamdar et al. (2018) | Y | Y | Y | N | N |
| Zhang and Ren (2016) | Y | Y | Y | N | N |
| Saha et al. (2016) | Y | Y | N | N | N |
| Ma et al. (2016) | Y | Y | Y | N | N |
| Taleizadeh et al. (2017b) | Y | Y | Y | N | N |
| Li et al. (2017) | Y | Y | Y | N | N |
| Granot and Sošić (2003) | N | N | Y | N | Y |
| Leng and Parlar (2009) | N | Y | Y | N | Y |
| Jena and Sarmah (2014) | Y | N | Y | N | Y |
| Zhang and Liu (2013) | N | Y | Y | N | Y |
| Noori-Daryan et al. (2017) | N | Y | Y | N | Y |
| Cui et al. (2007) | N | N | N | Y | N |
| Caliskan-Demirag et al. (2010) | N | N | N | Y | N |
| Yang et al. (2013) | N | N | N | Y | N |
| Du et al. (2014) | N | N | N | Y | N |
| Katok and Pavlov (2013) | N | N | N | Y | N |
| Liu et al. (2017b) | Y | N | N | Y | N |
| Ma et al. (2017) | Y | Y | N | Y | N |

| | | | | | |
|---|---|---|---|---|---|
| This research | Y | Y | Y | Y | Y |

More specifically, our paper is closely related to the studies conducted by Jena and Sarmah (2014) and Zhang and Liu (2013). The former applies cooperative games to CLSC coordination in a two-echelon setting with two competitive manufactures, but our game theoretic models are put in a three-echelon CLSC framework. On the other hand, while Zhang and Liu (2013) investigate a three-echelon green supply chain, their research does not account for remanufacturing or fairness concerns as we have considered in this paper. Moreover, Jena and Sarmah (2014) and Zhang and Liu (2013) only introduce one cooperative game model, the Shapley value approach, to coordinate their supply chains, but we put forward two additional cooperative game approaches to coordinate the CLSC.

Next, we present our model settings and assumptions.

## 3. Problem description

We consider a three-echelon CLSC consisting of a manufacturer (M), a distributor (D), and a fairness-minded retailer (R). To make the presentation gender-neutral, we hereafter refer to M as him, D as her, and R as it. In a decentralized setting, M produces new products, collects used products from the marketplace, and is responsible for remanufacturing. D then procures new and remanufactured products from M and wholesales them to R. R subsequently retails the products to the end market. In this decentralized model, M is modelled as the leader, followed by D, and lastly by R. Given R's relatively weaker position in this setting and consistent with the general observation that agents at disadvantage are often concerned with fairness (Ho and Su, 2009; Ho et al., 2014), we assume that R has distribution fairness concerns with its upstream partner D. Our key concern is to coordinate this three-echelon CLSC with R's fairness concerns by resorting to the cooperative game theory.

To derive the characteristic function form of the cooperative game, we need to examine all possible coalitions and their related equilibriums. Given the specific supply chain structure, we assume that D has an irreplaceable position in the CLSC so that M and R cannot skip her to form a coalition. With this assumption, four models are considered as shown in Fig. 1: a centralized model CC where a central planner makes all decisions, a decentralized model CD where each member makes his/her/its own decisions sequentially from M, to D, and to R, and two partially cooperative models MD and DR where two partial coalitions MD and DR are formed and make centralized decisions within the respective coalition. In the MD (DR) model, the partial coalition MD (DR) is treated as a new unified decision agent and the CLSC is essentially reduced to a two-echelon one. Under this setting, the partial coalition MD (DR) is modelled as the leader (follower) and the other partner R (M) is the follower (leader). Here, Models CC and CD, respectively, serve as top-line and bottom-line benchmark cases.

In this research, we assume that R's fairness concerns are reflected as an aversion to disadvantageous inequality relative to its immediate upstream partner (Ho and Su, 2009). Given this assumption, it is understandable that R's fairness concerns become irrelevant in Models CC and DR as there will be no financial transactions (and, hence, distribution inequality) between D and R. But in Models CD and MD, R shows fairness concerns with D and MD, respectively. As such, when R is an independent agent, it is fairness-minded and its objective is to maximize its utility and other agents (individual members or coalitions) aim at profit maximization. If R joins coalition DR or the grand coalition T, fairness concerns become irrelevant and all agents (members or coalitions) seek to maximize their profits.

Given the aforementioned model settings, we first derive equilibrium pricing, resulting quantities, and profits under the four models, CC, CD, MD, and DR. Then, the characteristic function form of the cooperative game is obtained based on the equilibrium results. Subsequently, three coordination mechanisms based on the cooperative game theory are proposed to allocate surplus profit among the three CLSC members. We then carry out numerical experiments to compare and evaluate the performance of the three coordination mechanisms, thereby garnering useful managerial insights for supply chain managers.

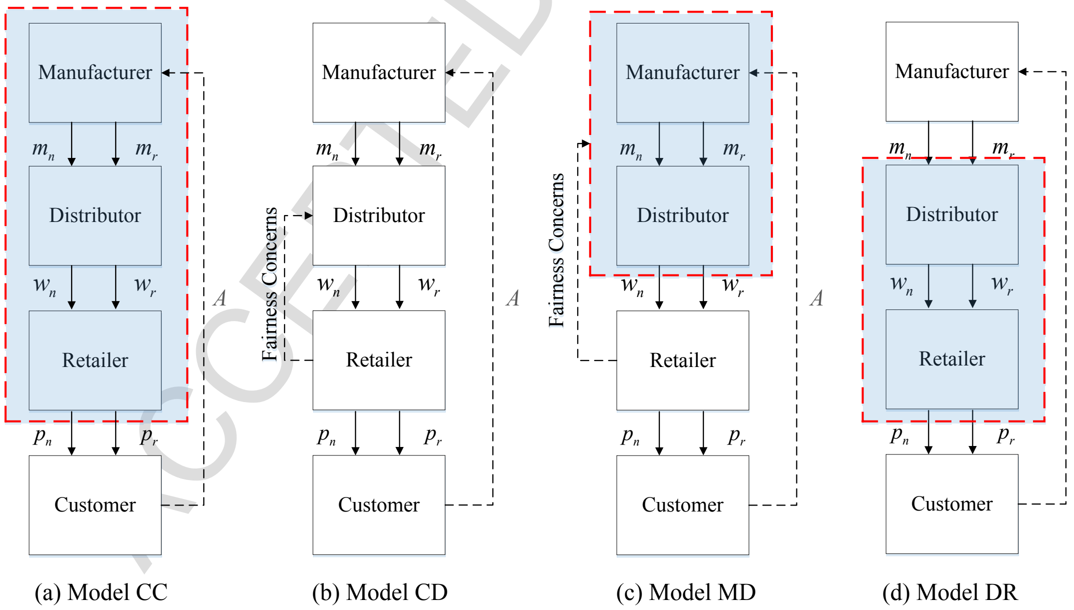



Fig.1. The non-cooperative and cooperative models of the three-echelon CLSC

## 4. Notation and assumptions

It is assumed that new and remanufactured products coexist in the same market (Souza, 2013; Xiong et al., 2013). Based on the problem description, we employ the following symbols and notation throughout this paper:

**Table 2.** Parameters and decision variables

| Symbol | Definition |
|---|---|
| $c_n / c_r$ | Unit production cost of new/remanufactured products |
| $m_n / m_r$ | Unit wholesale price of new/remanufactured products charged by M to D |
| $w_n / w_r$ | Unit wholesale price of new/remanufactured products paid charged by D to R |
| $p_n / p_r$ | Unit retail price of new/ remanufactured products |
| $q_n / q_r$ | Production quantity of new/remanufactured products |
| $A$ | Unit exogenous cost of recycling a used product |
| $\delta$ | Consumer value discount for remanufactured products |
| $\upsilon$ | Consumer's willingness-to-pay for new products |
| $\lambda$ | R's fairness concern parameter, where $\lambda \geq 0$ measures R's disutility of earning less than D |
| $\pi_j^i$ | Profit function of coalition $j$ in model $i$, $i \in \{CC, CD, MD, DR\}$ and $j = T$ (Model CC); *M*, *D*, *R* (Model CD); *MD*, *R* (Model MD); *M*, *DR* (Model DR), where $T$ is the grand coalition. |
| $\pi_j^{i(\varepsilon)}$ | The new or remanufactured product profit, where $\varepsilon \in \{n, r\}$ and $\pi_j^{i(n)} + \pi_j^{i(r)} = \pi_j^i$ |
| $u_R^h$ | R's fairness utility in model $h$, $h \in \{CD, MD\}$ |

To make the analysis tractable, we make the following assumptions in this research.

**Assumption 1.** Problem dynamics are captured in a steady one-period model.

This paper considers one-period interactions among CLSC members (Liu et al. (2017a). This assumption is consistent with existing research and has been widely used in literature (Örsdemir et al., 2014; Xiong et al., 2013; Yan et al., 2015; Zou et al., 2016). This assumption allows us to focus on the impact of R's fairness concerns on the CLSC members' pricing decisions and profit allocation schemes. We also assume that there exist plenty of used products for remanufacturing (Ma et al., 2017; Zou et al., 2016).

**Assumption 2.** Consumers are heterogeneous in their willingness-to-pay for a new product $\upsilon$, which is uniformly distributed between 0 and 1. Consumers' willingness-to-pay for a remanufactured product is a fraction $\delta$ of $\upsilon$, where $\delta \in [0,1)$.

The utilities that a consumer receives from new and remanufactured products are $u_n(\upsilon) = \upsilon - p_n$ and $u_r(\upsilon) = \delta\upsilon - p_r$, respectively. Following the utility maximization principle, if $u_n \geq \max\{u_r, 0\}$, consumers will purchase the new product, resulting in a new product demand function $q_n(p_n, p_r) = 1 - \frac{p_n - p_r}{1-\delta}$. If $u_r \geq \max\{u_n, 0\}$, consumers will purchase the remanufactured product, leading to a remanufactured product demand function $q_r(p_n, p_r) = \frac{p_n - p_r}{1-\delta} - \frac{p_r}{\delta}$ (Örsdemir et al., 2014; Yan et al., 2015).

**Assumption 3.** A remanufactured product is cheaper to produce, i.e., $0 < c_r < c_n < 1$.

Due to recycling of used parts and components, remanufacturing is typically less expensive than producing a new product, i.e. $0 < c_r < c_n$ (Ma et al., 2016; Zou et al., 2016). As consumers' maximum willingness-to-pay for new products is normalized to 1, the unit production cost $c_n$ must satisfy $c_n < 1$ to ensure positive demand for new products (Liu et al., 2017a)

**Assumption 4.** To ensure profitable remanufacturing, it is assumed that $A + c_r < \delta c_n$.

This assumption $A + c_r < \delta c_n$ allows M to enjoy a cost advantage so that he has an incentive to engage in recycling and remanufacturing (Atasu et al., 2008; Souza, 2013), and offers both new and remanufactured products. If $A + c_r \geq \delta c_n$, it is not economically viable for M to offer remanufactured products.

**Assumption 5.** D has an irreplaceable distribution channel so that M cannot form a coalition with R without D's participation.

This assumption is consistent with Leng and Parlar (2009) and Zhang and Liu (2013), where the midstream member in the supply chain is assumed indispensable.

**Assumption 6.** Only R has fairness concerns with its immediate upstream decision-maker (individual D or coalition MD). R has no fairness concerns with M directly and the concern level stays constant regardless of the upstream member being an individual or a coalition. The other members are fairness-neutral. This assumption is consistent with the general observation that agents at a disadvantageous position are usually concerned with fairness (Ho and Su, 2009; Ho et al., 2014). As R is a follower in our model setting and has a relatively weaker position in a CLSC, it is thus modelled to be the fairness-minded member in this research (Chen et al., 2017a).

## 5. The equilibrium analysis

Next, we derive the equilibrium results for the four base models, CC, CD, MD and DR.

### 5.1. The centralized model (Model CC)

We first consider the top-line benchmark case in which a centralized planner makes decisions for all CLSC members to maximize the system profit (see Fig. 1(a)). In this case, no financial transactions will be occurred between M and D or D and R, and the central planner sells to the end market directly. The channel profit function is formulated as:

$$\max_{p_n, p_r} \pi_T^{CC} = (p_n - c_n)q_n + (p_r - c_r - A)q_r . \tag{1}$$

Eq. (1) characterizes the CLSC channel profit as two components: the profit from new and remanufactured products. The central planner makes the retail pricing decisions for the two types of products to maximize the channel profit.

By first-order conditions, we have the following result.

**Proposition 1.** In the centralized model, the optimal selling prices, the resulting sales quantities of new and remanufactured products, and the channel profit are given as: $p_n^{*CC} = \frac{1+c_n}{2}$, $p_r^{*CC} = \frac{c_r + A + \delta}{2}$, $q_n^{*CC} = \frac{1-\delta-(c_n-c_r-A)}{2(1-\delta)}$, $q_r^{*CC} = \frac{\delta c_n - c_r - A}{2\delta(1-\delta)}$, and $\pi_T^{*CC} = \frac{(1-c_n)^2}{4} + \frac{(c_r + A - c_n\delta)^2}{4\delta(1-\delta)}$.

**Proof.** See Appendix A.

For notational convenience, let $K = \frac{(1-c_n)^2}{4} + \frac{(c_r + A - c_n\delta)^2}{4\delta(1-\delta)}$ and it is apparent that $K > 0$. Then, we rewrite $\pi_T^{*CC} = \tau_T^{CC*} K$, where $\tau_T^{*CC} = 1$. Without causing confusion, we hereafter shall refer to profit coefficient $\tau_j^{*i}$ as *j*'s profit in model *i*, $i \in \{CC, CD, MD, DR\}$, $j \in \{M, D, R, MD, DR, T\}$.

### 5.2. The decentralized model (Model CD)

In this model (see Fig. 1(b)), M and D are assumed to be fairness neutral while R has distributional fairness concerns with D. R cares about not only its own profit but also its profit relative to that of D. Therefore, R's utility function is given as

$$u_R^{CD} = \pi_R^{CD} - \lambda(\pi_D^{CD} - \pi_R^{CD}), \tag{2}$$

where $\lambda \geq 0$ is R's fairness concern parameter: the larger the $\lambda$, the more the R is concerned with distributional fairness (Chen et al., 2017a). Eq. (2) accounts for R's profit and disutility of its getting less profit than its upstream partner D. A more general model of fairness concerns considers both aversions to advantageous and disadvantageous inequality (e.g., Fehr and Schmidt (1999); Charness and Rabin (2002); Cui et al. (2007)). However, it has been revealed that aversion to advantageous inequality is not as common as that to disadvantageous inequality (Loewenstein et al., 1989). Ho and Su (2009)'s experiment even notes the absence of this aversion. As such, our research here follows this line of research by assuming that R's fairness concern is uni-directional. A large body of literature has adopted this idea and introduced similar utility functions with only disadvantageous inequality (Bolton, 1991; Chen et al., 2017; Ho et al., 2014; Nie and Du, 2017).

In this case, M and D maximize their profit while R pursues its utility maximization. The decision sequence is as follows: M first determines $m_n$ and $m_r$ for D to pay; then D sets $w_n$ and $w_r$ for R to pay; finally, R decides its retail prices $p_n$ and $p_r$ and sells the products to consumers. Accordingly, the three-echelon Stackelberg game consisting of M, D, and R is formulated as

$$\max_{m_n,m_r} \pi_M^{CD} = (m_n - c_n)q_n + (m_r - c_r - A)q_r$$
$$\begin{cases} s.t. \max_{w_n,w_r} \pi_D^{CD} = (w_n - m_n)q_n + (w_r - m_r)q_r , \\ \quad s.t. \max_{p_n,p_r} u_R^{CD} = \pi_R^{CD} - \lambda(\pi_D^{CD} - \pi_R^{CD}) \end{cases} \tag{3}$$

where $\pi_R^{CD} = (p_n - w_n)q_n + (p_r - w_r)q_r$. Eq. (3) characterizes the Stakelberg game for Model CD, where M moves first, followed by D, and then R. Here, M and D maximize their profits from new and remanufactured products and R maximizes its fairness-concerned utility, and decision variables are the wholesale and retail prices. This decentralized model is referred to as the Non-Cooperative Mechanism (NCM) and serves as a bottom-line benchmark for our comparative studies in Section 7. The following proposition furnishes the equilibrium result for this case.

**Proposition 2.** In Model CD, equilibrium prices are obtained as $m_n^{*CD} = \frac{1+c_n}{2}$, $m_r^{*CD} = \frac{c_r + A + \delta}{2}$, $w_n^{*CD} = \frac{3+c_n+\lambda(5+3c_n)}{4(1+2\lambda)}$, $w_r^{*CD} = \frac{c_r + A + 3\delta + 3(c_r + A)\lambda + 5\delta\lambda}{4(1+2\lambda)}$, $p_n^{*CD} = \frac{7+c_n}{8}$, and $p_r^{*CD} = \frac{c_r + A + 7\delta}{8}$. The resulting equilibrium sales quantities and profits are $q_n^{*CD} = \frac{1-\delta-(c_n - c_r - A)}{8(1-\delta)}$, $q_r^{*CD} = \frac{\delta c_n - c_r - A}{8\delta(1-\delta)}$, $\pi_M^{*CD} = \tau_M^{*CD}K$, $\pi_D^{*CD} = \tau_D^{*CD}K$, $\pi_R^{*CD} = \tau_R^{*CD}K$, and $\pi_T^{*CD} = \pi_M^{*CD} + \pi_D^{*CD} + \pi_R^{*CD} = \tau_T^{*CD} K$, where $\tau_M^{*CD} = \frac{1}{4}$, $\tau_D^{*CD} = \frac{1+\lambda}{8(1+2\lambda)}$, $\tau_R^{*CD} = \frac{1+4\lambda}{16(1+2\lambda)}$

and $\tau_T^{*CD} = \frac{7}{16}$.

**Proof.** The proof is furnished in Appendix B.

### 5.3. M and D form a coalition (MD)

In this model (see Fig. 1(c)), M and D form a coalition and are treated as a new decision-maker who decides $w_n$ and $w_r$. Subsequently, R sets its retail price $p_n$ and $p_r$. Similarly, coalition MD is assumed to be fairness-neutral, and R has fairness concerns with its relative profit distribution with coalition MD. Similar to $u_R^{CD}$, R's utility function in Model MD can be stated as

$$u_R^{MD} = \pi_R^{MD} - \lambda(\pi_{MD}^{MD} - \pi_R^{MD}),$$

where $\lambda$ is R's fairness concern level which is the same as that in Eq. (2) as per Assumption 6. In this case, coalition MD and R constitute a two-echelon Stackelberg game model where MD aims to maximize the profit of the coalition and R maximizes its utility $u_R^{MD}$. Similarly, as coalition MD works as a new decision-maker, there will be no financial transactions between M and D within the coalition. Therefore, this partial-coalition model is formulated as

$$\begin{aligned} &\max_{w_n, w_r} \pi_{MD}^{MD} = (w_n - c_n)q_n + (w_r - c_r - A)q_r \\ &s.t. \max_{p_n, p_r} u_R^{MD} = \pi_R^{MD} - \lambda(\pi_{MD}^{MD} - \pi_R^{MD}) \end{aligned} , \tag{4}$$

where $\pi_R^{MD} = (p_n - w_n)q_n + (p_r - w_r)q_r$. In this model, coalition MD is pooled together by two independent members M and D, so MD incurs the same production costs for the new and remanufactured products as M. Furthermore, due to this alliance between M and D, the pricing competition between these two members disappears. Instead, they make joint decisions ($w_n, w_r$) as an integrated agent to compete with the downstream member R. Given the optimal decisions and profit of MD, R shows fairness concerns and makes decisions to maximize its fairness utility.

The following proposition characterizes the equilibrium result.

**Proposition 3.** In Model MD, the equilibrium prices are given as $w_n^{*MD} = \frac{1+c_n+\lambda+3c_n\lambda}{2(1+2\lambda)}$, $w_r^{*MD} = \frac{c_r+A+\delta+3(c_r+A)\lambda+\delta\lambda}{2(1+2\lambda)}$, $p_n^{*MD} = \frac{3+c_n}{4}$, and

$p_r^{*MD} = \frac{c_r + A + 3\delta}{4}$. The resulting optimal sales quantities and profits are $q_n^{*MD} = \frac{1-\delta-(c_n - c_r - A)}{4(1-\delta)}$, $q_r^{*MD} = \frac{\delta c_n - c_r - A}{4\delta(1-\delta)}$, $\pi_{MD}^{*MD} = \tau_{MD}^{*MD} K$, $\pi_R^{*MD} = \tau_R^{*MD} K$, and $\pi_T^{*MD} = \tau_T^{*MD} K$, where $\tau_{MD}^{*MD} = \frac{1+\lambda}{2(1+2\lambda)}$, $\tau_R^{*MD} = \frac{1+4\lambda}{4(1+2\lambda)}$, and $\tau_T^{*MD} = \frac{3}{4}$.

**Proof.** The proof is included in Appendix C.

### 5.4. D and R form a coalition (DR)

In this model (as shown in Fig. 1(d)), D and R form a coalition. There will be no financial transactions between D and R, and as a result, there will be no profit distribution between D and R within this coalition, making R's fairness concerns irrelevant in this case. The coalition DR interacts with the Stackelberg leader M in a noncooperative setting. Hence, the model is formulated as

$$\begin{aligned} &\max_{m_n, m_r} \pi_M^{DR} = (m_n - c_n)q_n + (m_r - c_r - A)q_r \\ &s.t. \max_{p_n, p_r} \pi_{DR}^{DR} = (p_n - m_n)q_n + (p_r - m_r)q_r \end{aligned} . \tag{5}$$

In this setting, as R and D form a coalition and work together as a collective entity, this alliance removes the competition between D and R as well as R's fairness concerns. M makes the same pricing decisions as he does in Model D, and the coalition DR makes joint pricing decisions ($p_n, p_r$) to the final customers. The three-echelon decentralized model CD, is transformed into a two-echelon supply chain with M as the Stackelberg leader and coalition DR as the follower, and both maximize their respective profit.

This game is solved by backward induction and the equilibrium result is presented in Proposition 4.

**Proposition 4.** In Model DR, the equilibrium pricing decisions are obtained as $m_n^{*DR} = \frac{1+c_n}{2}$, $m_r^{*DR} = \frac{c_r + A + \delta}{2}$, $p_n^{*DR} = \frac{3+c_n}{4}$, and $p_r^{*DR} = \frac{c_r + A + 3\delta}{4}$. The resulting optimal quantities and profits are derived as $q_n^{*DR} = \frac{1-\delta-(c_n - c_r - A)}{4(1-\delta)}$, $q_r^{*DR} = \frac{\delta c_n - c_r - A}{4\delta(1-\delta)}$, $\pi_M^{*DR} = \tau_M^{*DR} K$, $\pi_{DR}^{*DR} = \tau_{DR}^{*DR} K$, and $\pi_T^{*DR} = \tau_T^{*DR} K$, where $\tau_M^{*DR} = \frac{1}{2}$, $\tau_{DR}^{*DR} = \frac{1}{4}$, and $\tau_T^{*DR} = \frac{3}{4}$.

**Proof.** The proof is given in Appendix D.

### 5.5. Comparative analysis of equilibrium results

By comparing the equilibrium results in Propositions 1-4, the following conclusions can be drawn.

**Proposition 5.** The wholesale prices of the new and remanufactured products in the three decentralized and partial-coalition models satisfy:

(1) $m_n^{*CD} = m_n^{*DR}$, $m_r^{*CD} = m_r^{*DR}$, and $\frac{\partial m_n^{*i}}{\partial \lambda} = \frac{\partial m_r^{*i}}{\partial \lambda} = 0$ where $i \in \{CD, DR\}$;

(2) $w_n^{*CD} > w_n^{*MD}$, $w_r^{*CD} > w_r^{*MD}$, $\frac{\partial w_n^{*MD}}{\partial \lambda} < \frac{\partial w_n^{*CD}}{\partial \lambda} < 0$, and $\frac{\partial w_r^{*MD}}{\partial \lambda} < \frac{\partial w_r^{*CD}}{\partial \lambda} < 0$.

**Proof.** The proof is given in Appendix E.

Proposition 5(1) shows that M's wholesale prices of new and remanufactured products in Model DR are the same as those in Model CD. This is understandable: From M's perspective, he only marks up the wholesale prices once regardless of the downstream partner being a single member D or a coalition DR. Therefore, we have $m_n^{*CD} = m_n^{*DR}$ and $m_r^{*CD} = m_r^{*DR}$. In addition, given that R only has fairness concerns with respect to D rather than M in Model CD (See Assumption 6) and it has no fairness concerns when it forms a coalition with D in Model DR, it is natural that M's wholesale pricing decisions are independent of R's fairness concern parameter $\lambda$ in these two models. So, one has $\frac{\partial m_n^{*i}}{\partial \lambda} = \frac{\partial m_r^{*i}}{\partial \lambda} = 0$ where $i \in \{CD, DR\}$.

Proposition 5(2) shows that the wholesale prices of new and remanufactured products charged by coalition MD are lower than those set by member D. This result is due to the cooperative strategy in Model MD that effectively eliminates the double marginalization between M and D, thereby allowing MD to charge lower wholesale prices while still enhancing the channel profit. Moreover, Proposition 5(2) demonstrates that the wholesale prices charged to R decrease in R's fairness concern parameter $\lambda$. This is natural as the more the R is concerned with distributional fairness, the more profit its upstream partner D or MD will transfer to R. Proposition 5(2) further reveals that $\frac{\partial w_n^{*MD}}{\partial \lambda} < \frac{\partial w_n^{*CD}}{\partial \lambda} < 0$ and $\frac{\partial w_r^{*MD}}{\partial \lambda} < \frac{\partial w_r^{*CD}}{\partial \lambda} < 0$. The reason is that coalition MD attains a profit in Model MD four times as much as a single member D obtains in Model CD ($\tau_D^{*CD} = \frac{1+\lambda}{8(1+2\lambda)}$ in Proposition 2 and $\tau_{MD}^{*MD} = \frac{1+\lambda}{2(1+2\lambda)}$ in Proposition 3). As such, given R's fairness concern parameter $\lambda$, coalition MD has much more room to lower the wholesale prices $w_n^{MD}, w_r^{MD}$ than D can reduce her wholesale prices $w_n^{CD}, w_r^{CD}$ for the new and remanufactured products.

**Proposition 6.** The retail prices of new and remanufactured products in the four models satisfy:

(1) $\frac{\partial p_n^{*i}}{\partial \lambda} = 0$ and $\frac{\partial p_r^{*i}}{\partial \lambda} = 0$, $i \in \{CC, CD, MD, DR\}$;

(2) $p_r^{*i} < p_n^{*i}$, $i \in \{CC, CD, MD, DR\}$;

(3) $p_n^{*CC} < p_n^{*MD} = p_n^{*DR} < p_n^{*CD}$ and $p_r^{*CC} < p_r^{*MD} = p_r^{*DR} < p_r^{*CD}$.

**Proof.** The proof is furnished in Appendix F.

Proposition 6(1) shows that R's fairness concerns do not affect the retail prices of new and remanufactured products in the four models. This is natural for Models CC and DR as R has no fairness concerns given that it cooperates with its upstream partner D in these two cases. For the other two models, CD and MD, in anticipation of R's fairness concerns, the upstream partner (member D or coalition MD) lowers the wholesale prices of new and remanufactured products to give up some profit margins (See Proposition 5), thereby allowing R to hold the retail prices steady and rake in more profit.

Proposition 6(2) concludes that the retail price of the remanufactured product is always lower than that of the new product in each of the four models. This is clear given that consumers have a lower willingness-to-pay for remanufactured products.

Proposition 6(3) compares the retail prices of new and remanufactured products across the four models. For both retail prices, the same relationship holds: Model CC has the lowest, Model CD has the highest, and Models MD and DR have the same value in the middle. This is due to the fact that Model CD has two mark-ups, first by M and then by D, Models MD and DR each has only one mark-up, and Model CC completely eliminates double marginalization. The different double-marginalization scenarios lead to distinct retail prices.

**Proposition 7.** The sale quantities of new and remanufactured products in the four models satisfy:

(1) $\frac{\partial q_n^{*i}}{\partial \lambda} = 0$ and $\frac{\partial q_r^{*i}}{\partial \lambda} = 0$, $i \in \{CC, CD, MD, DR\}$;

(2) $q_n^{*i} > 0$ if $1 + A + c_r > c_n + \delta$; otherwise, $q_n^{*i} = 0$, $i \in \{CC, CD, MD, DR\}$;

(3) $q_n^{*i} > q_r^{*i}$ if $(1+\delta)(A + c_r) > \delta(\delta + 2c_n - 1)$; otherwise, $q_n^{*i} \le q_r^{*i}$, $i \in \{CC, CD, MD, DR\}$;

(4) If $1 + A + c_r > c_n + \delta$, $q_n^{*CD} < q_n^{*MD} = q_n^{*DR} < q_n^{*CC}$ and $q_r^{*CD} < q_r^{*MD} = q_r^{*DR} < q_r^{*CC}$.

**Proof.** The proof is furnished in Appendix G.

Proposition 7(1) shows that R's fairness concerns have no impact on the sale quantities of the new and remanufactured products in the four models. This result is in parallel with Proposition 6(1) where R's fairness concerns do not affect the retail prices of these two products.

Proposition 7(2) indicates that positive demand for new products exists if and only if $1+A+c_r > c_n + \delta$. Otherwise, only remanufactured products will be offered by the CLSC.

Proposition 7(3) shows that a threshold $(1+\delta)(A+c_r) > \delta(\delta + 2c_n - 1)$ exists such that the sale quantity of new products is larger than that of the remanufactured products for the four models. It is worth noting that whether the quantity of remanufactured products exceeds that of new products depends on the structural parameters (i.e., $\delta$, $A$, $c_n$ and $c_r$) rather than the fairness concern parameter (i.e., $\lambda$). This is understandable as fairness concerns have no impact on the sale quantities of new and remanufactured products.

Proposition 7(4) compares the sale quantities of new and remanufactured products across the four models. We can observe that the sale quantities of these four models satisfy $q_n^{*CD} < q_n^{*MD} = q_n^{*DR} < q_n^{*CC}$ and $q_r^{*CD} < q_r^{*MD} = q_r^{*DR} < q_r^{*CC}$, corresponding to the relationships of the retail prices among the four models in Proposition 6(3), $p_n^{*CC} < p_n^{*MD} = p_n^{*DR} < p_n^{*CD}$ and $p_r^{*CC} < p_r^{*MD} = p_r^{*DR} < p_r^{*CD}$. Given that the sale quantity depends on the retail price, the lower the retailer price, the higher the sale quantity. Therefore, we have the highest sale quantity under Model CC, the lowest under Model CD, and the same middle value in Models MR and DR.

**Proposition 8.** The profits under the four models satisfy:

(1) $\tau_T^{*CD} < \tau_T^{*DR} = \tau_T^{*MD} < \tau_T^{*CC}$;

(2) $\tau_M^{*CD} = 0.25$, $\tau_D^{*CD} + \tau_R^{*CD} = 0.1875$, and $\dfrac{\partial \tau_D^{*CD}}{\partial \lambda} = -\dfrac{\partial \tau_R^{*CD}}{\partial \lambda} < 0$;

(3) $\tau_M^{*DR} > \tau_M^{*CD}$ and $\tau_{DR}^{*DR} > \tau_D^{*CD} + \tau_R^{*CD}$;

(4) $\tau_R^{*MD} > \tau_R^{*CD}$; If $0 < \lambda < 1$, $\tau_{MD}^{*MD} > \tau_M^{*CD} + \tau_D^{*CD}$, otherwise, $\tau_{MD}^{*MD} \le \tau_M^{*CD} + \tau_D^{*CD}$; $\dfrac{\partial \tau_{MD}^{*MD}}{\partial \lambda} = -\dfrac{\partial \tau_R^{*MD}}{\partial \lambda} < 0$.

**Proof.** The proof is furnished in Appendix H.

Proposition 8(1) clearly illustrates that double marginalization plays a significant role in channel profitability across the four models. Without it in Model CC, the profit attains the highest level; for the two partial-coalition models MD and DR, each is affected once with the same profit in the middle; Model CD achieves the lowest level since it is impacted twice.

For the decentralized model CD, Proposition 8(2) shows that M's profit stays constant at 0.25 and the total profit of D and R is always 0.1875. The relative profit distribution reflects M's leadership position in this CLSC model. In addition, when R's fairness concern level increases with a larger $\lambda$, it is understandable that D gives up more of her profit to appease R, leading to a higher profit for R and a lower profit for D. Proposition 8(2) further reveals that R's profit increases and D's profit decreases at the same rate when $\lambda$ increases, resulting in a constant total profit for D and R. This result attests that R's fairness concerns serve as a profit redistribution mechanism between R and its immediate upstream partner D.

Compared to Model CD, Proposition 8(3) demonstrates that M's profit is enhanced when D and R form a coalition. This can be deduced by examining Propositions 5 and 7: Proposition 5(1) confirms that M's wholesale prices of new and remanufactured products in Model DR are the same as those in Model CD, and Proposition 7(4) indicates higher market demand for new (if any) and remanufactured products in Model DR than that in Model CD. Therefore, we have $\tau_M^{*DR} > \tau_M^{*CD}$. Coalition DR achieves a higher profit than the total profit of D and R when they act independently in Model CD thanks to the elimination of double marginalization between D and R in Model DR as well as R's non-economic fairness concerns in Model CD.

When M and D form a coalition, Proposition 8(4) indicates that R attains a higher profit than that in Model CD regardless of the value of $\lambda$. It can be verified that R's unit profit margins of new and remanufactured products are both higher in Model MD than those in Model CD. Proposition 7(4) points out that the market demand for new (if any) and remanufactured products is higher in Model MD than that in Model CD. As such, R's profit in MD is higher than that in CD. For coalition MD, it is more complicated. Proposition 5(2) signifies that the coalition gives up more profit margin to R than member D does in Model CD. For smaller $\lambda \in (0,1)$, this extra concession does not hurt the coalition in the sense that both M and D are better off by cooperating than by acting independently. However, if R's fairness concerns are excessive (i.e., $\lambda > 1$), coalition MD becomes unstable as it is better off to dissolve the coalition by working on their own (i.e., $\tau_{MD}^{*MD} \le \tau_M^{*CD} + \tau_D^{*CD}$ if $\lambda \ge 1$ where equality holds at $\lambda = 1$). As for $\frac{\partial \tau_{MD}^{*MD}}{\partial \lambda} = -\frac{\partial \tau_R^{*MD}}{\partial \lambda} < 0$, its interpretation is similar to the case in

Proposition 8(2) and $\lambda$ serves as a profit redistribution vehicle between R and its upstream partner MD, which is a coalition here instead of an individual member D in Model CD.

**Proposition 9.** The optimal profits and sale quantities of new and remanufactured products under the four models satisfy:

(1) $\dfrac{\pi_j^{*i(n)}}{\pi_j^{*i(r)}} = \dfrac{\chi}{\gamma}$, where $\chi = \dfrac{(1-c_n)(1+A+c_r-\delta-c_n)}{1-\delta}$, $\gamma = \dfrac{(\delta-A-c_r)(\delta c_n - A - c_r)}{\delta(1-\delta)}$, $i \in \{CC, CD, MD, DR\}$

and $j$ corresponds to the relevant coalition(s) in a particular model $i$, where the coalition can be an individual member $M$, $D$, or $R$, a partial coalition $MD$ or $DR$, or the grand coalition $T$;

(2) $\dfrac{q_n^{*i}}{q_r^{*i}} = \dfrac{(\delta-A-c_r)\chi}{(1-c_n)\gamma}$, $i \in \{CC, CD, MD, DR\}$.

**Proof.** The proof is furnished in Appendix I.

Proposition 9 clearly shows that the ratio of the profit contribution from new products to that from remanufactured products is independent of R's fairness concern parameter and remains constant at $\dfrac{\pi_j^{i(n)}}{\pi_j^{i(r)}} = \dfrac{\chi}{\gamma}$ for each relevant coalition in the four models. While this result is natural for models CC and DR where R's fairness concerns are irrelevant, the impact of R's concerns on the ratio of the profit contribution from new products to that from remanufactured products is exactly cancelled out for each coalition involved in models CD and MD. As for sales quantities of new and remanufactured products, Proposition 7(1) clearly shows that they are both independent of R's fairness concern and, hence, the ratio $\dfrac{q_n^{*i}}{q_r^{*i}} = \dfrac{(\delta-A-c_r)\chi}{(1-c_n)\gamma}$ is also independent of $\lambda$.

**Proposition 10.** By examining the equilibrium solutions and profits in Models CD and MD when $\lambda > 0$ with those when $\lambda = 0$, one obtains the following result:

(1) $w_n^{*CD}\big|_{\lambda>0} < w_n^{*CD}\big|_{\lambda=0}$, $w_r^{*CD}\big|_{\lambda>0} < w_r^{*CD}\big|_{\lambda=0}$, $w_n^{*MD}\big|_{\lambda>0} < w_n^{*MD}\big|_{\lambda=0}$, $w_r^{*MD}\big|_{\lambda>0} < w_r^{*MD}\big|_{\lambda=0}$;

(2) $\pi_D^{*CD}\big|_{\lambda>0} < \pi_D^{*CD}\big|_{\lambda=0}$, $\pi_R^{*CD}\big|_{\lambda>0} > \pi_R^{*CD}\big|_{\lambda=0}$, $\pi_{MD}^{*MD}\big|_{\lambda>0} < \pi_{MD}^{*MD}\big|_{\lambda=0}$, $\pi_R^{*MD}\big|_{\lambda>0} > \pi_R^{*MD}\big|_{\lambda=0}$.

**Proof.** The proof is given in Appendix J.

Propositions 5-8 indicate that R's fairness concerns only affect the wholesale prices and related profit distributions under Models CD and MD. Proposition 10(1) shows that the upstream member D or coalition MD always offers lower wholesale prices for new and remanufactured products when R is fairness-minded compared to the case when R is fairness-neutral. Proposition 10(2) is natural as R's fairness concerns lead D in Model CD and MD in Model MD to transfer more of their profits to R. As such, fairness-minded R rakes in more profit than a fairness-neutral R at the expense of member D in Model CD and coalition MD in Model MD.

From Propositions 5-10, we conclude that R's fairness concerns do not affect the retail prices and sale quantities of the new and remanufactured products under the four models, leading to constant quantity and individual profit ratios of new to remanufactured products. R's fairness concerns serve as a profit redistribution tool between R and its immediate upstream partner D in Model CD and DR in Model DR but do not affect the total channel profit. We can also conclude that cooperation enhances channel profit, and the more cooperative the CLSC members are, the higher the channel profit. However, it remains unsettled how the resulting surplus profit should be allocated among the supply chain members. Next, we shall resort to the cooperative game theory to address this issue.

## 6. Cooperative game theoretic coordination mechanisms for CLSCs with R's fairness concerns

In this section, the cooperative game theory is employed to address fair allocation of surplus profit among the three CLSC members. This research defines fair allocation from both individual and collective rationality angles: A fair allocation scheme must enhance each member's individual profitability and collectively attain the maximum channel profit in the centralized case.

### 6.1. The characteristic function form of the cooperative game

A characteristic-function game is a pair $[N,v]$ consisting of a set of $n$ players $N=\{1,2,\cdots,n\}$ and a characteristic function $v$, mapping every coalition $S\subseteq N$ to a value $v(S)$ (Schmeidler, 1969). Given our CLSC setting, a cooperative game $[N,v]$ is established in the characteristic-function form in which $N=\{M,D,R\}$ represents the three CLSC members. Now we compute the characteristic values of all possible coalitions, $v(\varnothing)$, $v(M)$, $v(D)$, $v(R)$, $v(MD)$, $v(MR)$, $v(DR)$, and $v(MDR)$. According to the cooperative game theory, the characteristic value of a coalition is the minimum profit that it can gain based solely on its own effort (Leng and Parlar, 2009). In other words, the characteristic value of a coalition represents its bottom line and reflects its bargaining power in the cooperative game. Taking R's characteristic value $v(R)$ as an example. R's profits in Models CD and MD are $\tau_R^{*CD}K$ and $\tau_R^{*MD}K$, respectively. Hereafter, coefficient $\tau_j^{*i}$ is employed as a proxy of $\pi_j^{*i}$ in our analysis as it clearly indicates the profit allocation ratio for different coalitions as a fraction of the channel profit in the centralized case. As per Leng and Parlar (2009) and Nagarajan and Sošić (2008), the characteristic value is calculated as $v(R)=\min\{\tau_R^{*CD},\tau_R^{*MD}\}=\tau_R^{*CD}$. Similar to $v(R)$, other characteristic values are obtained as shown in Table 3. Note that the characteristic value of an empty coalition is naturally zero, $v(\varnothing)=0$ and thus omitted here. The value of coalition MR is zero owing to Assumption 5.

**Table 3.** The characteristic function of the cooperative game with R's fairness concerns

| Coalition | $(M)$ | $(D)$ | $(R)$ | $(MD)$ | $(MR)$ | $(DR)$ | $(MDR)$ |
|---|---|---|---|---|---|---|---|
| $v(S)$ | $\tau_M^{*CD}$ | $\tau_D^{*CD}$ | $\tau_R^{*CD}$ | $\tau_{MD}^{*MD}$ | 0 | $\tau_{DR}^{*DR}$ | $\tau_T^{*CC}$ |
| Value | $\frac{1}{4}$ | $\frac{1+\lambda}{8+16\lambda}$ | $\frac{1+4\lambda}{16+32\lambda}$ | $\frac{1+\lambda}{2+4\lambda}$ | 0 | $\frac{1}{4}$ | 1 |

### 6.2. Core guaranteed allocation mechanisms

Proposition 8 indicates that the channel achieves the maximum profit $K$ when the three CLSC members form the grand coalition in the centralized model. We aim to find a stable allocation scheme so that all members are better off if they are willing to coordinate their decisions. Since the characteristic values in Table 3 are furnished as profit coefficients, we denote $x_M$, $x_D$, and $x_R$ as the allocated profit coefficients to M, D, and R, respectively. A triple $(x_M,x_D,x_R)$ is called suitable if it satisfies the following two properties:

(1) Individual rationality: $x_M\geq v(M)$, $x_D\geq v(D)$, and $x_R\geq v(R)$;

(2) Collective rationality: $x_M+x_D+x_R=v(MDR)$.

A triple $x(v)=(x_M,x_D,x_R)$ satisfying the aforesaid properties is called an imputation of the cooperative game (Straffin (1993), and the set containing all nondominated imputations is denoted by $I(v)$. To obtain and analyze a unique allocation scheme, Gillies (1959) introduces the core of an $n$-person cooperative game in the characteristic-function form as $C(v)=\left\{x(v)\in I(v)\middle|\sum_{i\in S}x_i(v)\geq v(S)\text{ for all } S\subset N\right\}$. In the context of our research, this formula can be rewritten as $x_M\geq v(M)$, $x_D\geq v(D)$, $x_R\geq v(R)$, $x_M+x_D\geq v(MD)$, $x_M+x_R\geq v(MR)$, and $x_D+x_R\geq v(DR)$.

If the core is nonempty, its implied allocation scheme makes the grand coalition stable as no member is willing to leave the coalition unilaterally. Next, we shall propose three different coordination mechanisms based on the cooperative game theory, each suggesting a unique allocation scheme.

Next, three cooperative game mechanisms are proposed to allocate surplus profit due to cooperation among the three members. For notational convenience, denote $x_j^i$ as member *j*'s allocated profit coefficient under mechanism *i*, *i* = SVM (Shapley value mechanism), NSM (nucleolus solution mechanism), ESM (equal satisfaction mechanism); *j* = M, D, R.

**6.3. The Shapley Value Mechanism (SVM)**

Shapley value (Shapley, 1953) is a widely accepted profit allocation mechanism in cooperative games, which is simply the average marginal contribution of each player if this player enters all possible coalitions in a completely random order. Given the cooperative game $[N,v]$, $N=\{M,D,R\}$, the Shapley value of each CLSC member is determined as

$$x_j^{SVM}=\sum_{j\in S,S\subset N}w(|S|)[v(S)-v(S\setminus j)],\quad j=M,D,R, \tag{6}$$

where $v(S\setminus j)$ is the characteristic value of the coalition formed by all members in $S$ except for $j$, $|S|$ represents the number of players in coalition $S$, and $w(|S|)=\dfrac{(3-|S|)!(|S|-1)!}{3!}$ is the weight factor. It is worth noting that the Shapley value may not be in the core and will thus make the grand coalition unstable. Therefore, the objective of SVM is not only to derive the Shapely value but also to investigate whether it is in the core.

**6.4. The Nucleolus Solution Mechanism (NSM)**

Now we present the nucleolus solution concept that aims to minimize the largest degree of dissatisfaction of an allocation scheme (Schmeidler, 1969). By applying it to our cooperative game $[N,v]$, we calculate the nucleolus solution as follows:

$$\min \quad \mu. \tag{7}$$

$$s.t.\begin{cases} v(S)-\sum_{l\in S}x_l^{NSM}\le\mu \quad \text{for any} \quad S\subseteq N \\ x_M^{NSM}+x_D^{NSM}+x_R^{NSM}=\tau_T^C \end{cases}, \tag{8}$$

where $\mu$ can be treated as the "unhappiness" of the unhappiest player (Leng and Parlar, 2009). This linear programming model can be solved iteratively to find the nucleolus solution of the problem. It is noted that the nucleolus is always in the core if it exists.

**6.5. The Equal Satisfaction Mechanism (ESM)**

If a central planner wishes to encourage supply chain members to cooperate and form the grand coalition, one possible mechanism is to equalize their satisfaction by properly allocating the profit. Loosely speaking, satisfaction is defined as the ratio of the allocated profit to the ideal income. More specifically, denote member *j*'s ideal income by $r_j$, which is calculated by (Dai and Chen, 2012)

$$r_j = v(MDR) - v(MDR \setminus j) . \tag{9}$$

Then, given member $j$'s allocated profit $x_j$, its satisfaction can be defined as

$$s_j = x_j / r_j . \tag{10}$$

Understandably, the ideal income $r_j$ is usually unattainable, but it furnishes an upper bound for the allocated profit for player $j$ and it is reasonable for the player to expect a dividend of $v(MDR)$ (Tijs, 1987). It is apparent that the higher the $s_j$, the more satisfied the player is with the allocated profit.

Following the idea in Frisk et al. (2010)'s Equal Profit Method, we propose a new profit allocation mechanism that minimizes the maximum pairwise satisfaction difference, which is referred to as the Equal Satisfaction Mechanism (ESM). Given the cooperative game in the characteristic-function form $[N, v]$, the ESM is formulated as the following linear program:

$$\min f \tag{11}$$

$$\text{Subject to } f \geq s_g - s_h, \ \forall g, h = M, D, R \text{ and } g \neq h \tag{12}$$

$$\sum_{h \in S} x_h^{ESM} \geq v(S), \quad S \subset N \tag{13}$$

$$\sum_{h \in N} x_h^{ESM} = v(N) \tag{14}$$

$$x_R^{ESM} - \lambda(x_D^{ESM} - x_R^{ESM}) \geq v(R) - \lambda(v(D) - v(R)) \tag{15}$$

$$x_h^{ESM} \geq 0, h = M, D, R , \tag{16}$$

Constraint (12) measures pairwise satisfaction differences between any two members, which allows the objective function $f$ to minimize the largest satisfaction difference. Constraints (13) and (14) ensure that the optimal allocation is in the core. Constraint (15) guarantees that R's utility under ESM is no less than that under NCM. Therefore, the ESM allocation scheme aims to equalize all members' satisfaction while securing individual rationality, stability of the grand coalition, and improved utility for R.

## 7. Numerical experiment and comparative studies

In this section, by setting $\lambda = 0.9$, we first illustrate the solution process of profit allocation under the three coordination mechanisms presented in Section 6. Then, detailed comparative studies are carried out to examine how R's fairness concern parameter $\lambda$ affects profit allocations among the three CLSC members and R's utility under the three coordination mechanisms. This comparison sheds insights on the advantages and disadvantages of the three coordination mechanisms from different angles.

### 7.1. Solution process of profit allocations under the three coordination mechanisms

To obtain profit allocation schemes under the three coordination mechanisms in Section 6, we first set R's fairness concern parameter at $\lambda = 0.9$. By plugging this value into the characteristic function in Table 3, we have

**Table 4.** The characteristic values when $\lambda = 0.9$

| Coalition | $(M)$ | $(D)$ | $(R)$ | $(MD)$ | $(MR)$ | $(DR)$ | $(MDR)$ |
|---|---|---|---|---|---|---|---|
| $v(S)$ | $\tau_M^{*CD}$ | $\tau_D^{*CD}$ | $\tau_R^{*CD}$ | $\tau_{MD}^{*MD}$ | 0 | $\tau_{DR}^{*DR}$ | $\tau_T^{*CC}$ |
| Value | 0.25 | 0.0848 | 0.1027 | 0.3393 | 0 | 0.25 | 1 |

The next step is to check if the core of this game is empty (see Section 6.2 for more details). The core of this three-player game is computed by the toolbox TUGlab (Mirás Calvo, 2006) and graphically illustrated in the barycentric coordinates as shown in Fig. 2, where the nonempty core is specified as the shaded area.

The third step is to calculate the profit allocation schemes under the three coordination mechanisms. Given the characteristic values in Table 4, the following calculations can be carried out.

(1) By solving Eq. (6), we can obtain the allocation scheme under SVM as $x_M^{SVM} = 0.3586$, $x_D^{SVM} = 0.401$ and $x_R^{SVM} = 0.2403$.

(2) By solving the linear program given by (7) and (8), we derive the allocation scheme under NSM as $x_M^{NSM} = 0.4375$, $x_D^{NSM} = 0.2723$ and $x_R^{NSM} = 0.2902$.

(3) From Eq. (9), the ideal profit allocation coefficients are determined for the three members as $r_M = 0.75$, $r_D = 1$, and $r_R = 0.6607$. Subsequently, the allocation scheme under

ESM is derived by solving the linear program given in (11)-(16) as $x_M^{ESM} = 0.3111$, $x_D^{ESM} = 0.4148$, and $x_R^{ESM} = 0.2741$.

It is clear from Section 6.4 and 6.5 that the allocation schemes from NSM and ESM are automatically in the core if existent. The aforesaid calculations confirm their existence. So, our final step is to examine whether the SVM solution falls within the core as it is well known that the SVM always has a solution, but it is not necessarily in the core. Fig. 2 clearly shows that the allocation solutions under SVM, NSM and ESM are all located in the core. This indicates that the three allocation schemes here can all make the grand coalition stable.

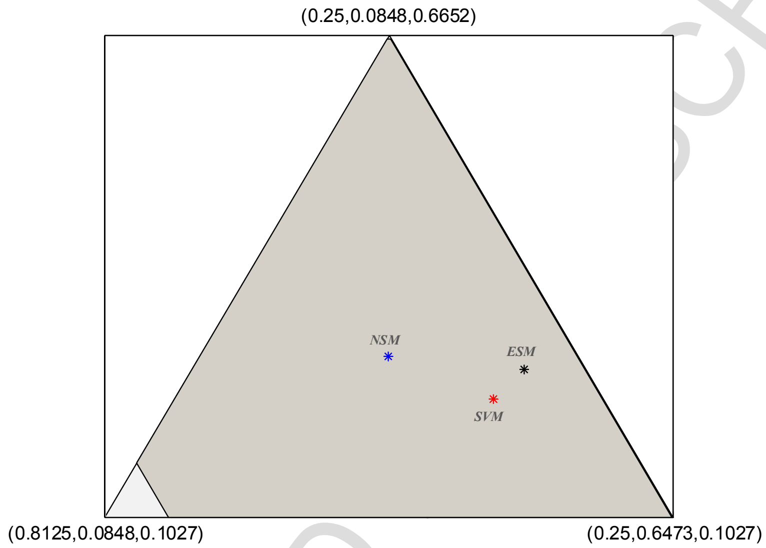


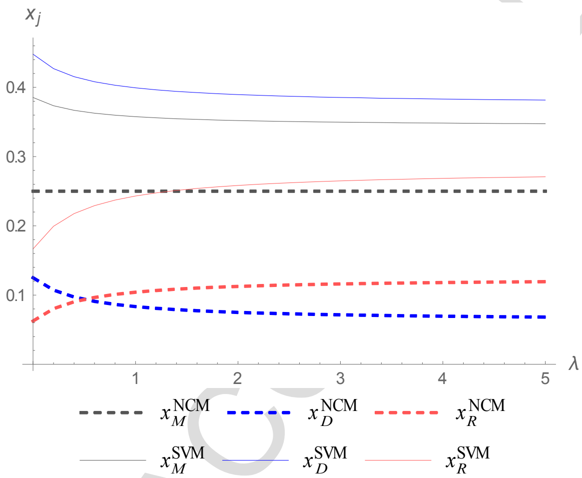

Fig. 2. Core and the solutions under the three coordination mechanisms ( $\lambda = 0.9$ )

### 7.2. Comparative studies: profit allocations and R's utility under the three coordination mechanisms

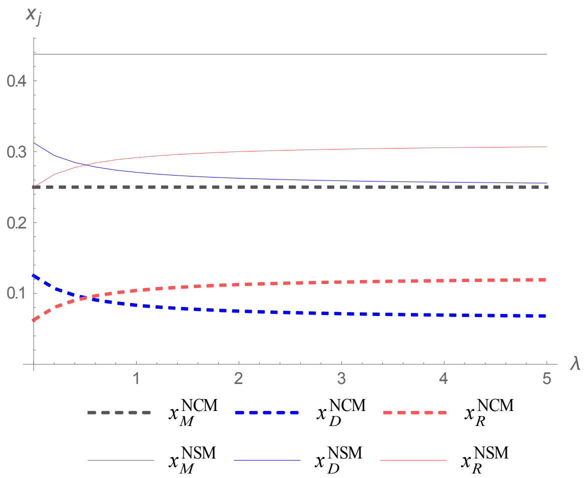
Fig. 2 in Section 7.1 confirms that, at $\lambda = 0.9$, the solutions from the three coordination mechanisms all fall within the core and, hence, result in unique profit allocation schemes for the three CLSC members. In this section, by changing the fairness concern parameter $\lambda$ from 0 to 5 in increment of 0.2, we carry out extensive comparative studies to assess the performance of the three coordination mechanisms relative to the benchmark case NCM from two aspects: profit allocations and R's utility. Our numerical studies verify that the characteristic functions for these $\lambda$ values all have non-empty cores and the corresponding profit allocation schemes are enforceable as they fall within the core and make the grand coalition stable.

#### 7.2.1. Comparison of profit allocations under the three coordination mechanisms

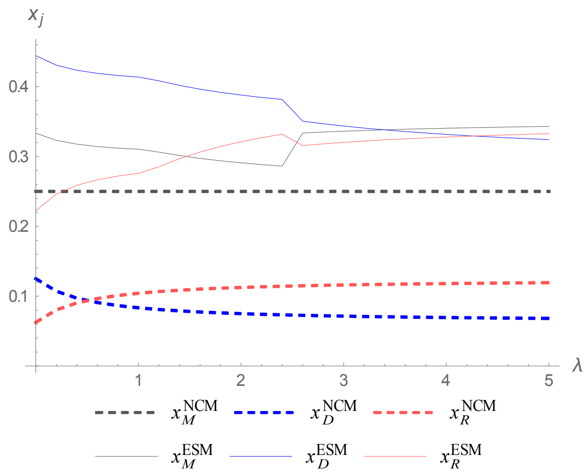
Table 5 lists the profit allocation results for the three members at different values of $\lambda$ under the three cooperative mechanisms and the benchmark noncooperative case NCM, which can be graphically illustrated in Fig. 3. This figure visually compares the profit allocation between each of the three coordination mechanisms and the NCM, where the solid lines show the results for the coordination mechanisms and dashed lines are for the NCM. In addition, the black, blue, and red lines signify the profits for M, D, and R, respectively. Fig. 3(a) compares the individual profits between the SVM and NCM, Fig. 3(b) illustrates the difference in profit allocation under NSM and NCM, Fig. 3(c) and 3(d) show the differences in profits between NCM and ESM with and without R's utility constraint, respectively. To differentiate the ESM with R's utility constraint from that without the constraint, we hereafter refer them to as ESM and NESM, respectively. All the profits in these figures are shown as a fraction of $K$. The dashed lines in the four sub-figures clearly demonstrate that, under NCM, M's profit stays constant as R is only concerned with distributional fairness with D, which does not affect M. When $\lambda = 0$, R has no fairness concerns and D's profit is higher than R's. When $\lambda$ increases, R's profit increases and D's profit decreases. R's and D's profit lines insect at $\lambda$ = 0.5. Fig. 3 clearly demonstrates that M, D, and R all have higher profits under the three coordination mechanisms compared to those under NCM. Collectively, our calculations indicate that SVM, NSM, and ESM with and without R's utility constraint can fully coordinate the CLSC by achieving the optimal channel profit under the centralized setting.



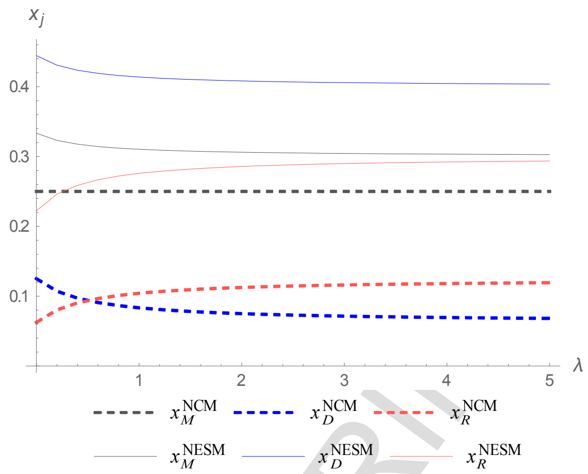

(a) Individual profits under SVM and NCM




(b) Individual profits under NSM and NCM




(c) Individual profits under ESM and NCM




(d) Individual profits under NESM and NCM

Fig.3. Individual profit comparisons between the three coordination mechanisms and NCM

More specifically, Fig. 3(a) indicates that, under SVM, D is allocated the largest share of the channel profit, followed by M and, then, R. This differs from the NCM case where M takes the largest share due to its leadership role in the CLSC. This result is due to the allocation principle under SVM, which is based on the average marginal contributions of the three members by entertaining different coalitions. Given Assumption 5, it is impossible for M and R to form a coalition owing to D's irreplaceable position in the CLSC. This is characterized by $v(MR)=0$, which decreases M's and R's marginal contributions but increases D's marginal contribution. Under this assumption, D basically takes over the leadership role and, hence, is allocated the largest share of the total profit. Furthermore, as SVM is derived based on the characteristic function, the allocated profits under SVM reflect the general trend of the characteristic function. In NCM, it is understandable that $v(D)$ and $v(MD)$ decrease in R's fairness concern parameter $\lambda$ while $v(R)$ increases in $\lambda$. As such, the allocated profits for M, D, and R under SVM in Fig. 3(a) clearly follow the same pattern: the lines change more rapidly when $\lambda$ is small and get flatter when $\lambda$ becomes bigger.

Fig. 3(b) demonstrates that the profit allocation under NSM resonates the trend under NCM: M's profit stays constant, R's profit increases in $\lambda$, while D's profit decreases in $\lambda$ and intersects R's profit line at $\lambda=0.5$. Another feature is that, compared to NCM, each member under NSM receives an identical profit increment of $0.1875K$ regardless of the value of $\lambda$. This result is due to the surplus profit distribution principle under NSM, which iteratively minimizes the "unhappiness" of the unhappiest player. To fairly increase every member's happiness under the cooperative framework, NSM evenly splits the channel profit increment $0.5625K$ among M, D, and R compared to NCM. Thus, each member receives an equal surplus profit of $0.1875K$.

Fig. 3(c) and 3(d) compare profit allocations between ESM and NCM, where Fig. 3(c) includes R's utility constraint (15) and Fig. 3(d) drops it. Without accounting for R's utility constraint (15), Fig. 3(d) shows a similar pattern of profit allocations as Fig. 3(a) for the three members, $x_D^{SVM} > x_M^{SVM} > x_R^{SVM}$, which is consistent with the relationship of the three members' ideal income coefficients (i.e., $r_D > r_M > r_R$). The difference is that the equalization of satisfactions shifts R's profit up and M's profit down. By incorporating R's utility constraint (15) in ESM, Fig. 3(c) confirms that the same relationship $x_D^{ESM} > x_M^{ESM} > x_R^{ESM}$ only holds for small enough $\lambda$. This result is reasonable as the basic idea of ESM is to minimize the satisfaction differences among the three members. When $\lambda < 1.08809$, Fig. 3(c) shows that R's profit increases and D's and M's profits decrease at rapid paces. Once $\lambda$ extends beyond 1.08809, R's utility constraint (15) becomes binding, and the rate of profit change decreases slightly for the three members. When $\lambda$ further increases to $\lambda \approx 2.485$, the equal satisfaction constraint (12) starts kicking in. The joint effect of constraints (12) and (15) causes D's and R's profits to jump down and M's profit to jump up, helping to close the satisfaction gaps among the three members. Thereafter, M's and R's profits increase and D's profit decreases in $\lambda$ at much slower paces. For large enough $\lambda$, we have $x_M^{ESM} > x_R^{ESM} > x_D^{ESM}$ in Fig. 3(c), as opposed to $x_D^{NESM} > x_M^{NESM} > x_R^{NESM}$ for all $\lambda$ in Fig. 3(d). In summary, Fig. 3(c) and Fig. 3(d) clearly show how R's utility constraint (15) in ESM affects the surplus profit allocation among the three members under ESM.

These numerical studies confirm that the aforesaid three coordination mechanisms can fully coordinate the CLSC by achieving the optimal channel profit under the centralized case. In addition, Fig. 3 clearly shows that the resulting surplus profit allocation schemes can improve profitability for every CLSC member. As each coordination mechanism follows a unique principle to encourage cooperation, different CLSC members tend to gain differently under these three mechanisms. Nevertheless, it is further verified that these allocation schemes fall in the core of the cooperative game, making the grand coalition stable and furnishing viable options for the three members to collaborate with each other for individual and collective betterment.

Table 5 also displays each member's increased profits for different values of $\lambda$ under each coordination mechanism compared to the benchmark case NCM. Based on the results from this numerical experiment, one can obtain the average increased profits for the three members under the three coordination mechanisms as listed in the last row of Table 5 and graphically illustrated in Fig. 4. From Fig. 4, it is clear that, except for the case NSM when the three members are equally rewarded by an equal increased profit, D and R are, on average, better off than M. The primary reasons are due to D's indispensable position in this supply chain and R's fairness concerns. Fig. 4 clearly shows that D, on average, achieves a higher profit enhancement than R does, implying that D's irreplaceable position in the CLSC plays a more significant role in profit allocation than R's fairness concerns do. On the other hand, M is still incentivized to join the grand coalition as his profit will also be enhanced under these coordination mechanisms compared to NCM.

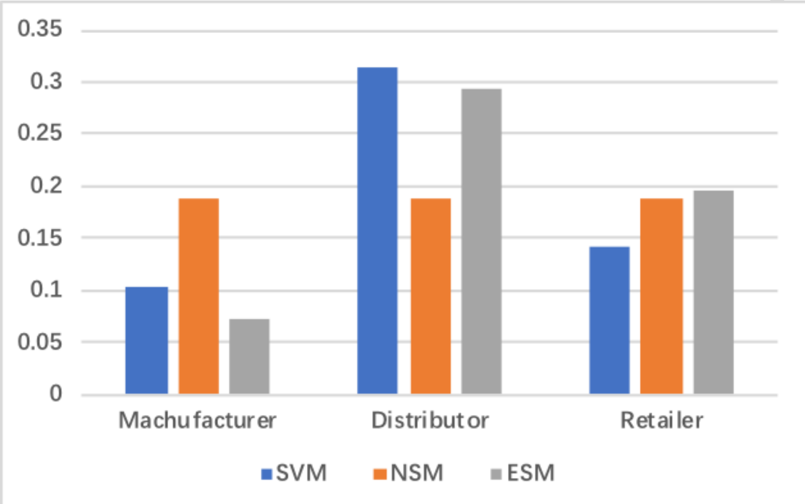



Fig.4. Comparisons of each member's average increased profits relative to the NCM

### 7.2.2. Comparison of R's utility under the three coordination mechanisms

Fig. 5 graphically displays how R's utility changes with its fairness concern parameter $\lambda$ under the benchmark case NCM and the three coordination mechanisms.

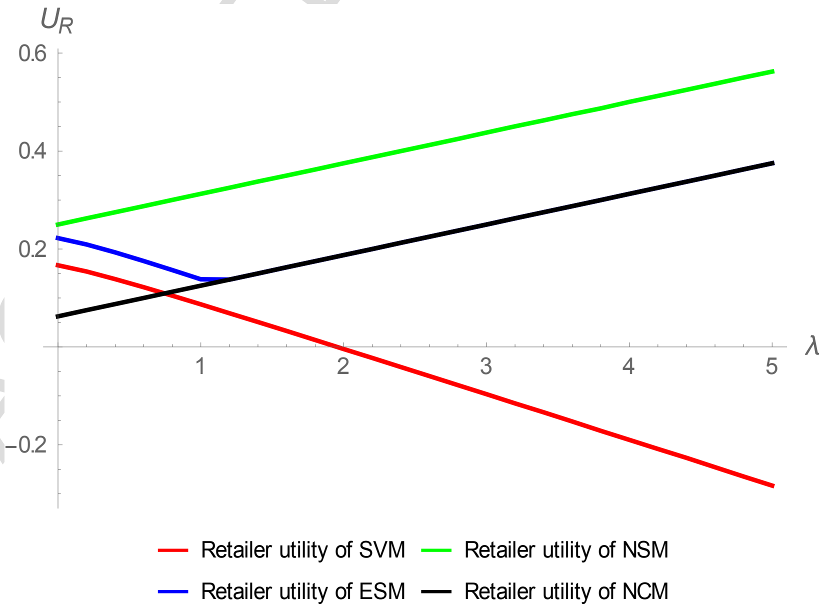



Fig.5. Comparisons of R's utilities

**Table 5.** Profit allocations for the three members under NCM and the three coordination mechanisms

| $\lambda$ | Manufacturer | | | | | | | Distributor | | | | | | | Retailer | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | NCM | SVM | IP | NSM | IP | ESM | IP | NCM | SVM | IP | NSM | IP | ESM | IP | NCM | SVM | IP | NSM | IP | ESM | IP |
| 0 | 0.2500 | 0.3854 | 0.1354 | 0.4375 | 0.1875 | 0.3333 | 0.0833 | 0.1250 | 0.4479 | 0.3229 | 0.3125 | 0.1875 | 0.4444 | 0.3194 | 0.0625 | 0.1667 | 0.1042 | 0.2500 | 0.1875 | 0.2222 | 0.1597 |
| 0.2 | 0.2500 | 0.3735 | 0.1235 | 0.4375 | 0.1875 | 0.3231 | 0.0731 | 0.1071 | 0.4271 | 0.3200 | 0.2946 | 0.1875 | 0.4308 | 0.3236 | 0.0804 | 0.1994 | 0.1190 | 0.2679 | 0.1875 | 0.2462 | 0.1658 |
| 0.4 | 0.2500 | 0.3669 | 0.1169 | 0.4375 | 0.1875 | 0.3176 | 0.0676 | 0.0972 | 0.4155 | 0.3183 | 0.2847 | 0.1875 | 0.4235 | 0.3263 | 0.0903 | 0.2176 | 0.1273 | 0.2778 | 0.1875 | 0.2588 | 0.1685 |
| 0.6 | 0.2500 | 0.3627 | 0.1127 | 0.4375 | 0.1875 | 0.3143 | 0.0643 | 0.0909 | 0.4081 | 0.3172 | 0.2784 | 0.1875 | 0.4190 | 0.3281 | 0.0966 | 0.2292 | 0.1326 | 0.2841 | 0.1875 | 0.2667 | 0.1701 |
| 0.8 | 0.2500 | 0.3598 | 0.1098 | 0.4375 | 0.1875 | 0.3120 | 0.0620 | 0.0865 | 0.4030 | 0.3165 | 0.2740 | 0.1875 | 0.4160 | 0.3295 | 0.1010 | 0.2372 | 0.1362 | 0.2885 | 0.1875 | 0.2720 | 0.1710 |
| 1 | 0.2500 | 0.3576 | 0.1076 | 0.4375 | 0.1875 | 0.3103 | 0.0603 | 0.0833 | 0.3993 | 0.3160 | 0.2708 | 0.1875 | 0.4138 | 0.3305 | 0.1042 | 0.2431 | 0.1389 | 0.2917 | 0.1875 | 0.2759 | 0.1717 |
| 1.2 | 0.2500 | 0.3560 | 0.1060 | 0.4375 | 0.1875 | 0.3063 | 0.0563 | 0.0809 | 0.3964 | 0.3155 | 0.2684 | 0.1875 | 0.4084 | 0.3275 | 0.1066 | 0.2475 | 0.1409 | 0.2941 | 0.1875 | 0.2853 | 0.1787 |
| 1.4 | 0.2500 | 0.3547 | 0.1047 | 0.4375 | 0.1875 | 0.3013 | 0.0513 | 0.0789 | 0.3942 | 0.3153 | 0.2664 | 0.1875 | 0.4018 | 0.3228 | 0.1086 | 0.2511 | 0.1425 | 0.2961 | 0.1875 | 0.2969 | 0.1883 |
| 1.6 | 0.2500 | 0.3537 | 0.1037 | 0.4375 | 0.1875 | 0.2973 | 0.0473 | 0.0774 | 0.3924 | 0.3150 | 0.2649 | 0.1875 | 0.3963 | 0.3190 | 0.1101 | 0.2540 | 0.1439 | 0.2976 | 0.1875 | 0.3064 | 0.1963 |
| 1.8 | 0.2500 | 0.3528 | 0.1028 | 0.4375 | 0.1875 | 0.2938 | 0.0438 | 0.0761 | 0.3909 | 0.3148 | 0.2636 | 0.1875 | 0.3918 | 0.3157 | 0.1114 | 0.2563 | 0.1449 | 0.2989 | 0.1875 | 0.3144 | 0.2030 |
| 2 | 0.2500 | 0.3521 | 0.1021 | 0.4375 | 0.1875 | 0.2909 | 0.0409 | 0.0750 | 0.3896 | 0.3146 | 0.2625 | 0.1875 | 0.3879 | 0.3129 | 0.1125 | 0.2583 | 0.1458 | 0.3000 | 0.1875 | 0.3211 | 0.2086 |
| 2.2 | 0.2500 | 0.3515 | 0.1015 | 0.4375 | 0.1875 | 0.2885 | 0.0385 | 0.0741 | 0.3885 | 0.3144 | 0.2616 | 0.1875 | 0.3846 | 0.3105 | 0.1134 | 0.2600 | 0.1466 | 0.3009 | 0.1875 | 0.3269 | 0.2135 |
| 2.4 | 0.2500 | 0.3509 | 0.1009 | 0.4375 | 0.1875 | 0.2863 | 0.0363 | 0.0733 | 0.3876 | 0.3143 | 0.2608 | 0.1875 | 0.3817 | 0.3085 | 0.1142 | 0.2615 | 0.1473 | 0.3017 | 0.1875 | 0.3320 | 0.2177 |
| 2.6 | 0.2500 | 0.3505 | 0.1005 | 0.4375 | 0.1875 | 0.3337 | 0.0837 | 0.0726 | 0.3868 | 0.3142 | 0.2601 | 0.1875 | 0.3506 | 0.2780 | 0.1149 | 0.2628 | 0.1479 | 0.3024 | 0.1875 | 0.3157 | 0.2008 |
| 2.8 | 0.2500 | 0.3501 | 0.1001 | 0.4375 | 0.1875 | 0.3350 | 0.0850 | 0.0720 | 0.3860 | 0.3140 | 0.2595 | 0.1875 | 0.3469 | 0.2749 | 0.1155 | 0.2639 | 0.1484 | 0.3030 | 0.1875 | 0.3181 | 0.2026 |
| 3 | 0.2500 | 0.3497 | 0.0997 | 0.4375 | 0.1875 | 0.3362 | 0.0862 | 0.0714 | 0.3854 | 0.3140 | 0.2589 | 0.1875 | 0.3436 | 0.2722 | 0.1161 | 0.2649 | 0.1488 | 0.3036 | 0.1875 | 0.3202 | 0.2041 |
| 3.2 | 0.2500 | 0.3494 | 0.0994 | 0.4375 | 0.1875 | 0.3373 | 0.0873 | 0.0709 | 0.3849 | 0.3140 | 0.2584 | 0.1875 | 0.3407 | 0.2697 | 0.1166 | 0.2658 | 0.1492 | 0.3041 | 0.1875 | 0.3221 | 0.2055 |
| 3.4 | 0.2500 | 0.3491 | 0.0991 | 0.4375 | 0.1875 | 0.3382 | 0.0882 | 0.0705 | 0.3843 | 0.3138 | 0.2580 | 0.1875 | 0.3381 | 0.2676 | 0.1170 | 0.2666 | 0.1496 | 0.3045 | 0.1875 | 0.3237 | 0.2068 |
| 3.6 | 0.2500 | 0.3488 | 0.0988 | 0.4375 | 0.1875 | 0.3390 | 0.0890 | 0.0701 | 0.3839 | 0.3138 | 0.2576 | 0.1875 | 0.3357 | 0.2656 | 0.1174 | 0.2673 | 0.1499 | 0.3049 | 0.1875 | 0.3252 | 0.2079 |
| 3.8 | 0.2500 | 0.3486 | 0.0986 | 0.4375 | 0.1875 | 0.3398 | 0.0898 | 0.0698 | 0.3835 | 0.3137 | 0.2573 | 0.1875 | 0.3336 | 0.2638 | 0.1177 | 0.2679 | 0.1502 | 0.3052 | 0.1875 | 0.3266 | 0.2089 |
| 4 | 0.2500 | 0.3484 | 0.0984 | 0.4375 | 0.1875 | 0.3405 | 0.0905 | 0.0694 | 0.3831 | 0.3137 | 0.2569 | 0.1875 | 0.3317 | 0.2622 | 0.1181 | 0.2685 | 0.1504 | 0.3056 | 0.1875 | 0.3279 | 0.2098 |
| 4.2 | 0.2500 | 0.3482 | 0.0982 | 0.4375 | 0.1875 | 0.3411 | 0.0911 | 0.0691 | 0.3828 | 0.3137 | 0.2566 | 0.1875 | 0.3299 | 0.2608 | 0.1184 | 0.2691 | 0.1507 | 0.3059 | 0.1875 | 0.3290 | 0.2106 |
| 4.4 | 0.2500 | 0.3480 | 0.0980 | 0.4375 | 0.1875 | 0.3416 | 0.0916 | 0.0689 | 0.3824 | 0.3135 | 0.2564 | 0.1875 | 0.3283 | 0.2594 | 0.1186 | 0.2696 | 0.1510 | 0.3061 | 0.1875 | 0.3300 | 0.2114 |
| 4.6 | 0.2500 | 0.3478 | 0.0978 | 0.4375 | 0.1875 | 0.3422 | 0.0922 | 0.0686 | 0.3821 | 0.3135 | 0.2561 | 0.1875 | 0.3269 | 0.2582 | 0.1189 | 0.2700 | 0.1511 | 0.3064 | 0.1875 | 0.3310 | 0.2121 |
| 4.8 | 0.2500 | 0.3477 | 0.0977 | 0.4375 | 0.1875 | 0.3426 | 0.0926 | 0.0684 | 0.3819 | 0.3135 | 0.2559 | 0.1875 | 0.3255 | 0.2571 | 0.1191 | 0.2704 | 0.1513 | 0.3066 | 0.1875 | 0.3319 | 0.2128 |
| 5 | 0.2500 | 0.3475 | 0.0975 | 0.4375 | 0.1875 | 0.3431 | 0.0931 | 0.0682 | 0.3816 | 0.3134 | 0.2557 | 0.1875 | 0.3242 | 0.2560 | 0.1193 | 0.2708 | 0.1515 | 0.3068 | 0.1875 | 0.3327 | 0.2134 |
| AIP | | | 0.1043 | | 0.1875 | | 0.0725 | | | 0.3151 | | 0.1875 | | 0.2931 | | | 0.1431 | | 0.1875 | | 0.1969 |

IP: increased profit compared to the case under NCM; AIP: Average increased profit compared to the case under NCM

For the benchmark case NCM where the three members make their independent decisions, as R's fairness concerns bring down D's profit and bump up R's profit, R's utility understandably increases in $\lambda$ as shown in the increasing black line in Fig. 5. As all the three coordination mechanisms enhance R's profitability to various degrees, it is natural that R's utility is higher under SVM, NSM, and ESM than that under NCM when its fairness concerns are not too strong. As a matter of fact, given that NSM equally splits the surplus profit among the three members, R's utility under NSM is simply shifted up by a constant compared to the NCM case, which is plotted as a parallel increasing green line in Fig. 5. Under ESM, R's utility first decreases in $\lambda$ when it is small. At $\lambda \approx 1.08809$, R's utility constraint becomes binding and the blue line coincides with the black line in Fig. 5. As for SVM, D receives the highest profit allocation among the three members. Although R's profit is enhanced, its fairness concerns drives its utility down as $\lambda$ increases. At $\lambda \approx 0.746711$, R's utility breaks even with the case in NCM. Thereafter, R's utility suffers a loss under SVM compared to that under NCM. When $\lambda$ further increases beyond $\lambda > 2.82542$, its utility even turns negative as shown in the red declining line in Fig. 5.

Given R's noneconomic fairness concerns, one can see that profit enhancement does not necessarily lead to higher utility for R under the three coordination mechanisms. From R's utility perspective, NSM brings in the highest utility gain, while SVM and ESM only benefit R's utility when R is not so concerned with distributional fairness.

The analytical and numerical studies shed important managerial insights on operating the CLSC. Firstly, the equilibrium analysis in Section 5 confirms the conventional wisdom: With R's fairness concerns, it remains true that the more cooperative the CLSC, the higher the channel profit. This result motivates us to consider coordinating the supply chain system from a cooperative game perspective instead of relying on traditionally contracting design based on a noncooperative framework. Secondly, the three proposed cooperative game approaches are viable mechanisms to coordinate the CLSC system as each offers a unique allocation scheme that satisfies both individual and collective rationality. As different coordination mechanisms benefit the three members differently, the resulting allocation schemes furnish diverse perspectives and can serve as sensible starting points for the supply chain partners to negotiate a final deal based on their relative power standing in the system. Thirdly, for the fairness-minded R, its enhanced profit is not necessarily translated into a higher utility compared to the benchmark noncooperative mechanism, especially when its fairness concern level is high and SVM is adopted as the basis for allocating surplus profit. In this case, D should be prepared to give up more profit to entice the retailer to remain in the grand coalition for the betterment of every member (higher profit for M and D and higher utility for R).

## 8. Conclusions

Based on a three-echelon CLSC consisting of M, D, and R, this paper takes R's fairness concerns into account under four scenarios: the centralized (CC), decentralized (CD), and two partial-coalition models (MD and DR). Equilibrium analyses are first carried out for these four models. Analytical results reveal that the more decentralized the supply chain system, the more the channel profit suffers. In Models CD and MD where R's fairness concerns are in effect, the corresponding parameter $\lambda$ serves as a tool to redistribute the profits between R and its immediate upstream partner (D or MD) without affecting the relevant channel profitability. In addition, it is understandable that the larger the $\lambda$, the more the profit will be transferred to R. Based on the equilibrium results, the characteristic function of the cooperative game is derived. Subsequently, three coordination mechanisms, the Shapley value, nucleolus solution, and equal satisfaction are proposed to allocate surplus profit among the three CLSC members. Numerical studies confirm that the resulting surplus profit allocation schemes satisfy both individual and collective rationality and fall in the core of the cooperative game, thereby making the grand coalition stable and suggesting viable options to coordinate the CLSC system. Comparative analyses are carried out to examine how R's fairness concern parameter $\lambda$ affects profit allocations among the three CLSC members and R's resulting utility under the three coordination mechanisms. While all members achieve higher profits under the three coordination mechanisms compared to the decentralized case, numerical experiment reveals that D receives the highest profit share under SVM, M gets the largest profit under NSM, and the three CLSC members tend to be more equitably rewarded under ESM. From R's utility perspective, its enhanced profit does not always translate into higher utility: While R always enjoys higher utility under NSM than that under NCM, for large $\lambda$, it tends to suffer a utility loss under SVM compared to NCM, thereby deterring the fairness-concerned R from joining the grand coalition.

Significant opportunities exist for future research. For instance, this paper only considers coordination mechanisms based on the cooperative game methods. It is well known that different contracting forms based on non-cooperative game models can also coordinate supply chains. It is a worthy topic to carry out a comparative study between these two classes of coordination models. In addition, this research considers a three-echelon CLSC with one member at each echelon. It is worthwhile to extend this research to a more complex CLSC network structure with two or more members at one or more echelons. In this article, fairness concerns are characterized by R's aversion to disadvantageous inequality and the other two members are assumed to be fairness-neutral. It would be interesting to incorporate other members' fairness concerns as well as peer-induced fairness concerns (Ho et al., 2014) into the model and examine their impact on the supply chain operations and surplus profit allocation.

**Appendix A. Proof of Proposition 1**

Substituting the demand functions $q_n(p_n, p_r)$ and $q_r(p_n, p_r)$ into the profit function $\pi_T^{CC}$ and taking partial derivatives of the channel profit with respect to retail prices, we have $\frac{\partial^2 \pi_T^{CC}}{\partial p_n^2} = -\frac{2}{1-\delta} < 0$, $\frac{\partial^2 \pi_T^{CC}}{\partial p_r^2} = -\frac{2}{\delta(1-\delta)} < 0$, and $\frac{\partial^2 \pi_T^{CC}}{\partial p_n \partial p_r} = \frac{2}{1-\delta}$. Therefore, $\frac{\partial^2 \pi_T^{CC}}{\partial p_n^2}\frac{\partial^2 \pi_T^{CC}}{\partial p_r^2} - (\frac{\partial^2 \pi_T^{CC}}{\partial p_n \partial p_r})^2 = \frac{4}{\delta(1-\delta)} > 0$, the profit function $\pi_T^{CC}$ is thus strictly joint concave in $p_n$ and $p_r$. This confirms that Model CC has a unique optimal solution.

Given the first-order conditions $\frac{\partial \pi_T^{CC}}{\partial p_n} = 1 + \frac{c_n - c_r - 2(p_n - p_r)}{1-\delta} = 0$ and $\frac{\partial \pi_T^{CC}}{\partial p_r} = \frac{c_r - 2p_r - \delta(c_n - 2p_n)}{\delta(1-\delta)} = 0$, we derive the optimal decisions $p_n^{*CC} = \frac{1+c_n}{2}$ and $p_r^{*CC} = \frac{c_r + A + \delta}{2}$. Then, plugging them into the demand functions yields the resulting optimal production quantities for new and remanufactured products as $q_n^{*CC} = \frac{1-\delta-(c_n - c_r - A)}{2(1-\delta)}$ and $q_r^{*CC} = \frac{\delta c_n - c_r - A}{2\delta(1-\delta)}$. Subsequently, one can determine the optimal total profit as $\pi_T^{*CC} = \frac{(1-c_n)^2}{4} + \frac{(c_r + A - c_n\delta)^2}{4\delta(1-\delta)} = K$.

This proves Proposition 1.

**Appendix B. Proof of Proposition 2**

In Model CD, the supply chain members make decisions independently, where M and D maximize their individual profit functions and R maximizes its utility function. This is modelled as a Stackelberg game where M first makes his wholesale price decisions $m_n$ and $m_r$, then D determines her wholesale prices $w_n$ and $w_r$, and finally, R sets its retail prices of new and remanufactured products $p_n$ and $p_r$ and sells them to the end market. The backward induction method is used to solve this model as follows.

First, substituting demand functions $q_n(p_n, p_r)$ and $q_r(p_n, p_r)$ into R's utility function $u_R^{CD}$ and taking partial derivatives, one has $\frac{\partial^2 u_R^{CD}}{\partial p_n^2} = -\frac{2(1+\lambda)}{1-\delta} < 0$, $\frac{\partial^2 u_R^{CD}}{\partial p_r^2} = -\frac{2(1+\lambda)}{\delta(1-\delta)} < 0$, and $\frac{\partial^2 u_R^{CD}}{\partial p_n \partial p_r} = \frac{2(1+\lambda)}{1-\delta} > 0$. As such, one confirms that $\frac{\partial^2 u_R^{CD}}{\partial p_n^2}\frac{\partial^2 u_R^{CD}}{\partial p_r^2} - (\frac{\partial^2 u_R^{CD}}{\partial p_n \partial p_r})^2 = \frac{4(1+\lambda)^2}{\delta(1-\delta)} > 0$, which implies that R's utility function $u_R^{CD}$ is strictly joint concave in $p_n$ and $p_r$, and $u_R^{CD}$ has a unique optimal solution. By the first-order conditions $\frac{\partial u_R^{CD}}{\partial p_n} = 0$ and $\frac{\partial u_R^{CD}}{\partial p_r} = 0$, we obtain R's optimal response functions as $p_n^{CD*}(w_n, w_r) = \frac{1 + w_n + \lambda(1 - m_n + 2w_n)}{2(1+\lambda)}$ and $p_r^{CD*}(w_n, w_r) = \frac{w_r + \delta + \lambda(\delta - m_r + 2w_r)}{2(1+\lambda)}$. Plugging them into demand functions $q_n(p_n, p_r)$ and $q_r(p_n, p_r)$, we have the optimal quantities of new and remanufactured products $q_n^{CD*}(w_n, w_r)$ and $q_r^{CD*}(w_n, w_r)$ as functions of D's wholesale prices $w_n$ and $w_r$.

Substituting $q_n^{CD*}(w_n, w_r)$ and $q_r^{CD*}(w_n, w_r)$ into D's profit function $\pi_D^{CD}$ and solving the first-order conditions $\frac{\partial \pi_D^{CD}}{\partial w_n} = 0$ and $\frac{\partial \pi_D^{CD}}{\partial w_r} = 0$, we get D's optimal decisions as: $w_n^{CD*}(m_n, m_r) = \frac{1 + m_n + \lambda(1 + 3m_n)}{2(1+2\lambda)}$ and $w_r^{CD*}(m_n, m_r) = \frac{m_r + \delta + \lambda(\delta + 3m_r)}{2(1+2\lambda)}$. Plugging them into demand functions $q_n(w_n, w_r)$ and $q_r(w_n, w_r)$, we can express the optimal quantities of new and remanufactured products $q_n^{CD*}(m_n, m_r)$ and $q_r^{CD*}(m_n, m_r)$ as functions of M's wholesale prices $m_n$ and $m_r$.

Substituting $q_n^{CD*}(m_n, m_r)$ and $q_r^{CD*}(m_n, m_r)$ into M's profit function $\pi_M^{CD}$ and solving the first-order conditions $\frac{\partial \pi_M^{CD}}{\partial m_n} = 0$ and $\frac{\partial \pi_M^{CD}}{\partial m_r} = 0$, we derive M's optimal wholesale prices as $m_n^{CD*} = \frac{1 + c_n}{2}$ and $m_r^{CD*} = \frac{c_r + \delta + A}{2}$.

Subsequently, we determine D's optimal wholesale prices of new and remanufactured products as $w_n^{*CD} = \frac{3+c_n+5\lambda+3c_n\lambda}{4(1+2\lambda)}$ and $w_r^{*CD} = \frac{c_r+A+3\delta+3(c_r+A)\lambda+5\delta\lambda}{4(1+2\lambda)}$, and R's corresponding retail prices as $p_n^{*CD} = \frac{7+c_n}{8}$ and $p_r^{*CD} = \frac{c_r+A+7\delta}{8}$. Plugging them into the demand functions yields the quantities of new and remanufactured products as $q_n^{*CD} = \frac{1-\delta-(c_n-c_r-A)}{8(1-\delta)}$ and $q_r^{*CD} = \frac{\delta c_n-c_r-A}{8\delta(1-\delta)}$. From there, we calculate the individual and channel equilibrium profits as $\pi_M^{*CD} = \frac{1}{4}K$, $\pi_D^{*CD} = \frac{1+\lambda}{8(1+2\lambda)}K$, $\pi_R^{*CD} = \frac{1+4\lambda}{16(1+2\lambda)}K$, and $\pi_T^{*CD} = \frac{7}{16}K$, respectively.

Proposition 2 is thus confirmed.

**Appendix C. Proof of Proposition 3**

In Model MD, coalition MD and R constitute a two-echelon Stackelberg game model where the coalition is the leader and R the follower. Similarly, backward induction is employed to solve this model.

Substituting demand functions $q_n(p_n, p_r)$ and $q_r(p_n, p_r)$ into R's utility function $u_R^{MD}$ and taking partial derivatives, one has $\frac{\partial^2 u_R^{MD}}{\partial p_n^2} = -\frac{2(1+\lambda)}{1-\delta} < 0$, $\frac{\partial^2 u_R^{MD}}{\partial p_r^2} = -\frac{2(1+\lambda)}{\delta(1-\delta)} < 0$, and $\frac{\partial^2 u_R^{MD}}{\partial p_n \partial p_r} = \frac{2(1+\lambda)}{1-\delta} > 0$. It is trivial to confirm that $\frac{\partial^2 u_R^{MD}}{\partial p_n^2}\frac{\partial^2 u_R^{MD}}{\partial p_r^2} - (\frac{\partial^2 u_R^{MD}}{\partial p_n \partial p_r})^2 = \frac{4(1+\lambda)^2}{\delta(1-\delta)} > 0$. This indicates that R's utility function $u_R^{MD}$ is strictly joint concave in $p_n$ and $p_r$ and has a unique optimal solution. Solving the first-order conditions $\frac{\partial u_R^{MD}}{\partial p_n} = 0$ and $\frac{\partial u_R^{MD}}{\partial p_r} = 0$ leads to R's optimal response functions $p_n^{MD*}(w_n, w_r) = \frac{1+w_n+\lambda(1-c_n+2w_n)}{2(1+\lambda)}$ and $p_r^{MD*}(w_n, w_r) = \frac{w_r+\delta+\lambda(\delta-c_r-A+2w_r)}{2(1+\lambda)}$. Plugging them into the demand functions yields the optimal new and remanufactured product quantities $q_n^{MD*}(w_n, w_r)$ and $q_r^{MD*}(w_n, w_r)$ as functions of the coalition's wholesale prices $w_n$ and $w_r$.

Next, substituting $q_n^{MD*}(w_n, w_r)$ and $q_r^{MD*}(w_n, w_r)$ into coalition MD's profit function $\pi_{MD}^{MD}$ and taking partial derivatives, we have $\frac{\partial^2 \pi_{MD}^{MD}}{\partial w_n^2} = -\frac{1+2\lambda}{(1-\delta)(1+\lambda)} < 0$, $\frac{\partial^2 \pi_{MD}^{MD}}{\partial w_r^2} = -\frac{1+2\lambda}{\delta(1-\delta)(1+\lambda)} < 0$, and $\frac{\partial^2 \pi_{MD}^{MD}}{\partial w_n \partial w_r} = \frac{1+2\lambda}{(1-\delta)(1+\lambda)} > 0$. This confirms that $\frac{\partial^2 \pi_{MD}^{MD}}{\partial w_n^2}\frac{\partial^2 \pi_{MD}^{MD}}{\partial w_n^2} - (\frac{\partial^2 \pi_{MD}^{MD}}{\partial w_n \partial w_r})^2 = \frac{(1+2\lambda)^2}{\delta(1-\delta)(1+\lambda)^2} > 0$ and, hence, coalition MD's profit function $\pi_{MD}^{MD}$ is strictly joint concave in $w_n$ and $w_r$ and has a unique optimal solution. By the first-order conditions $\frac{\partial \pi_{MD}^{MD}}{\partial w_n} = 0$ and $\frac{\partial \pi_{MD}^{MD}}{\partial w_r} = 0$, we get MD's optimal wholesale prices $w_n^{MD*} = \frac{1+c_n+\lambda(1+3c_n)}{2(1+2\lambda)}$ and $w_r^{MD*} = \frac{c_r + A + \delta + \lambda(3c_r + 3A + \delta)}{2(1+2\lambda)}$.

Plugging them into R's response functions results in the optimal retail prices of new and remanufactured products $p_n^{*MD} = \frac{3+c_n}{4}$ and $p_r^{*MD} = \frac{c_r + A + 3\delta}{4}$. Subsequently, we obtain the quantities of new and remanufactured products as $q_n^{*MD} = \frac{1-\delta-(c_n - c_r - A)}{4(1-\delta)}$ and $q_r^{*MD} = \frac{c_n\delta - c_r - A}{4\delta(1-\delta)}$ as well as coalition MD's, R's and the channel profits as $\pi_{MD}^{*MD} = \frac{1+\lambda}{2(1+2\lambda)}K$, $\pi_R^{*MD} = \frac{1+4\lambda}{4(1+2\lambda)}K$, and $\pi_T^{*MD} = \frac{3}{4}K$.

We then complete the proof of Proposition 3.

**Appendix D. Proof of Proposition 4**

In Model DR, M and coalition DR constitute a two-echelon Stackelberg game model with M being the leader and DR the follower. Once again, backward induction is applied to obtain equilibrium solutions.

Plugging demand functions $q_n(p_n, p_r)$ and $q_r(p_n, p_r)$ into coalition DR's profit function and taking partial derivatives, we have $\frac{\partial^2 \pi_{DR}^{DR}}{\partial p_n^2} = -\frac{2}{1-\delta} < 0$, $\frac{\partial^2 \pi_{DR}^{DR}}{\partial p_r^2} = -\frac{2}{\delta(1-\delta)} < 0$, and $\frac{\partial^2 \pi_{DR}^{DR}}{\partial p_n \partial p_r} = \frac{2}{1-\delta} > 0$. This implies that $\frac{\partial^2 \pi_{DR}^{DR}}{\partial p_n^2}\frac{\partial^2 \pi_{DR}^{DR}}{\partial p_r^2} - (\frac{\partial^2 \pi_{DR}^{DR}}{\partial p_n \partial p_r})^2 = \frac{4}{\delta(1-\delta)} > 0$. So DR's profit function $\pi_{DR}^{DR}$ is strictly joint concave in $p_n$ and $p_r$ and has a unique optimal solution.

By examining the first-order conditions $\frac{\partial \pi_{DR}^{DR}}{\partial p_n} = 0$ and $\frac{\partial \pi_{DR}^{DR}}{\partial p_r} = 0$, we obtain R's optimal response functions $p_n^{DR*}(m_n, m_r) = \frac{1+m_n}{2}$ and $p_r^{DR*}(m_n, m_r) = \frac{m_r + \delta}{2}$. Accordingly, we can express the optimal quantities of new and remanufactured products as $q_n^{DR*}(m_n, m_r) = \frac{1 - m_n + m_r - \delta}{2(1-\delta)}$ and $q_r^{DR*}(m_n, m_r) = \frac{m_r - \delta m_n}{2\delta(1-\delta)}$, respectively.

Substituting $q_n^{DR*}(m_n, m_r)$ and $q_r^{DR*}(m_n, m_r)$ into M's profit function $\pi_M^{DR}$ and taking partial derivatives, one confirms that $\frac{\partial^2 \pi_M^{DR}}{\partial m_n^2} = -\frac{1}{1-\delta} < 0$, $\frac{\partial^2 \pi_M^{DR}}{\partial m_r^2} = -\frac{1}{\delta(1-\delta)} < 0$, and $\frac{\partial^2 \pi_M^{DR}}{\partial m_n \partial m_r} = \frac{1}{1-\delta} > 0$, implying that $\frac{\partial^2 \pi_{DR}^{DR}}{\partial p_n^2} \frac{\partial^2 \pi_{DR}^{DR}}{\partial p_r^2} - (\frac{\partial^2 \pi_{DR}^{DR}}{\partial p_n \partial p_r})^2 = \frac{1}{\delta(1-\delta)} > 0$. So, $\pi_M^{DR}$ has a unique optimal solution. By the first-order conditions $\frac{\partial \pi_{DR}^{DR}}{\partial m_n} = 0$ and $\frac{\partial \pi_{DR}^{DR}}{\partial m_r} = 0$, we obtain M's optimal wholesale prices $m_n^{DR*} = \frac{1+c_n}{2}$ and $m_r^{DR*} = \frac{c_r + \delta + A}{2}$.

One can then determine DR's optimal retail prices of new and remanufactured products as $p_n^{*DR} = \frac{3+c_n}{4}$ and $p_r^{*DR} = \frac{c_r + A + 3\delta}{4}$, thereby obtaining equilibrium quantities of new and remanufactured products as $q_n^{*DR} = \frac{1 - \delta - (c_n - c_r - A)}{4(1-\delta)}$ and $q_r^{*DR} = \frac{\delta c_n - c_r - A}{4\delta(1-\delta)}$ as well as the profits of M, coalition DR and the channel as $\pi_M^{*DR} = \frac{1}{4}K$, $\pi_{DR}^{*DR} = \frac{1}{2}K$, and $\pi_T^{*DR} = \frac{3}{4}K$, respectively.

Proposition 4 is thus proved.

**Appendix E. Proof of Proposition 5**

Comparing M's wholesale prices of new and remanufactured products in Models CD and DR in Propositions 2 and 4, we can get:

$$m_n^{*CD} - m_n^{*DR} = 0, \; m_r^{*CD} - m_r^{*DR} = 0.$$

Similarly, by examining D's wholesale prices in Model CD and MD's wholesale prices in Model MD, it is easy to see that

$$w_n^{*CD} - w_n^{*MD} = \frac{(1-c_n)(1+3\lambda)}{4(1+2\lambda)} > 0, \; w_r^{*CD} - w_r^{*MD} = -\frac{(c_r - \delta)(1+3\lambda)}{4+8\lambda} > 0 .$$

Taking partial derivatives of the optimal wholesale prices of new and remanufactured products with respect to R's fairness concern parameter $\lambda$, we have:

$$\frac{\partial w_n^{*CD}}{\partial \lambda} = -\frac{1-c_n}{4(1+2\lambda)^2} < 0, \quad \frac{\partial w_n^{*MD}}{\partial \lambda} = -\frac{1-c_n}{2(1+2\lambda)^2} < 0, \quad \text{and} \quad \frac{\partial w_n^{*CD}}{\partial \lambda} - \frac{\partial w_n^{*MD}}{\partial \lambda} = \frac{1-c_n}{4(1+2\lambda)^2} > 0;$$

$$\frac{\partial w_r^{*CD}}{\partial \lambda} = \frac{c_r + A - \delta}{4(1+2\lambda)^2} < 0, \quad \frac{\partial w_r^{*MD}}{\partial \lambda} = \frac{c_r + A - \delta}{2(1+2\lambda)^2} < 0, \quad \text{and} \quad \frac{\partial w_r^{*CD}}{\partial \lambda} - \frac{\partial w_r^{*MD}}{\partial \lambda} = -\frac{c_r + A - \delta}{4(1+2\lambda)^2} > 0;$$

$$\frac{\partial m_n^{*i}}{\partial \lambda} = \frac{\partial m_r^{*i}}{\partial \lambda} = 0 \text{ where } i \in \{CD, DR\}.$$

Proposition 5 is then verified.

**Appendix F. Proof of Proposition 6**

Taking partial derivatives of the retail prices of new and remanufactured products with respect to R's fairness concern parameter $\lambda$, it is easy to confirm that

$$\frac{\partial p_n^{*i}}{\partial \lambda} = \frac{\partial p_r^{*i}}{\partial \lambda} = 0, \ i \in \{CC, CD, MD, DR\}.$$

Subtracting the retail price of the remanufactured product from that of the new product under each of the four models, it is trivial to verify that

$$p_n^{*CC} - p_r^{*CC} = \frac{1-\delta + c_n - c_r - A}{2} > 0, \ p_n^{*CD} - p_r^{*CD} = \frac{7(1-\delta) + c_n - c_r - A}{8} > 0,$$

$$p_n^{*MD} - p_r^{*MD} = p_n^{*DR} - p_r^{*DR} = \frac{3(1-\delta) + c_n - c_r - A}{4} > 0.$$

Comparing the optimal retail prices of new and remanufactured products across the four models in Propositions 1-4, one can confirm that

$$p_n^{*CD} - p_n^{*DR} = \frac{1-c_n}{8} > 0, \ p_n^{*DR} - p_n^{*MD} = 0, \text{ and } p_n^{*MD} - p_n^{*CC} = \frac{1-c_n}{4} > 0;$$

$$p_r^{*CD} - p_r^{*DR} = \frac{\delta - c_r - A}{8} > 0, \ p_r^{*DR} - p_r^{*MD} = 0, \text{ and } p_r^{*MD} - p_r^{*CC} = \frac{\delta - c_r - A}{4} > 0.$$

Proposition 6 is thus proved.

**Appendix G. Proof of Proposition 7**

Taking partial derivatives of the sale quantities of new and remanufactured products with respect to R's fairness concern parameter $\lambda$, it is easy to confirm that

$$\frac{\partial q_n^{*i}}{\partial \lambda} = \frac{\partial q_r^{*i}}{\partial \lambda} = 0, \ i \in \{CC, CD, MD, DR\}.$$

Given the optimal sale quantities of new products $q_n^{*CC} = \dfrac{1-\delta-(c_n-c_r-A)}{2(1-\delta)}$ under Model CC, we have $q_n^{*CD} = \dfrac{1}{4}q_n^{*CC}$ and $q_n^{*MD} = q_n^{*DR} = \dfrac{1}{2}q_n^{*CC}$. If $1+A+c_r > c_n+\delta$, $q_n^{*i} > 0$ where $i \in \{CC, CD, MD, DR\}$. Otherwise, $q_n^{*i} = 0$

Subtracting the sale quantities of remanufactured products from that of new products under each of the four models, it is trivial to verify that

$q_n^{*CC} - q_r^{*CC} = \dfrac{(1+\delta)(A+c_r)-\delta(\delta+2c_n-1)}{2\delta-2\delta^2}$, $q_n^{*CD} - q_r^{*CD} = \dfrac{(1+\delta)(A+c_r)-\delta(\delta+2c_n-1)}{8\delta-8\delta^2}$, $q_n^{*MD} - q_r^{*MD} = q_n^{*DR} - q_r^{*DR} = \dfrac{(1+\delta)(A+c_r)-\delta(\delta+2c_n-1)}{4\delta-4\delta^2}$. When $(1+\delta)(A+c_r) > \delta(\delta+2c_n-1)$, we have $q_n^{*i} > q_r^{*i}$, otherwise, $q_n^{*i} \le q_r^{*i}$.

Comparing the optimal sale quantities of new and remanufactured products across the four models in Propositions 1-4, we can confirm that

$q_n^{*DR} - q_n^{*CD} = \dfrac{1-\delta-(c_n-c_r-A)}{8(1-\delta)}$, $q_n^{*DR} - q_n^{*MD} = 0$, and $q_n^{*CC} - q_n^{*MD} = \dfrac{1-\delta-(c_n-c_r-A)}{4(1-\delta)}$, implying that $q_n^{*CD} < q_n^{*MD} = q_n^{*DR} < q_n^{*CC}$ if $1+A+c_r > c_n+\delta$;

$q_r^{*DR} - q_r^{*CD} = \dfrac{\delta c_n - c_r - A}{8\delta(1-\delta)} > 0$, $q_r^{*DR} - q_r^{*MD} = 0$, and $q_r^{*CC} - q_r^{*MD} = \dfrac{\delta c_n - c_r - A}{4\delta(1-\delta)} > 0$, indicating that $q_r^{*CD} < q_r^{*MD} = q_r^{*DR} < q_r^{*CC}$.

Proposition 7 is thus proved.

**Appendix H. Proof of Proposition 8**

By examining the optimal channel profits under different models in Propositions 1-4, it is obvious that

$$\tau_T^{*CC} - \tau_T^{*MD} = \frac{1}{4} > 0,\ \tau_T^{*MD} - \tau_T^{*DR} = 0, \text{ and } \tau_T^{*DR} - \tau_T^{*CD} = \frac{5}{16} > 0;$$

Taking partial derivatives of D's and R's optimal profits with respect to R's fairness concern parameter $\lambda$ under Model CD, one has

$$\frac{\partial \tau_D^{*CD}}{\partial \lambda} = -\frac{1}{8(1+2\lambda)^2} < 0 \text{ and } \frac{\partial \tau_R^{*CD}}{\partial \lambda} = \frac{1}{8(1+2\lambda)^2} > 0.$$

Subtracting M's profit under Model DR from that under Model CD, we can get:

$$\tau_M^{*DR} - \tau_M^{*CD} = \frac{1}{4} > 0 .$$

Subtracting the total profit of D and R under Model CD from coalition DR's profit under Model DR, we have:

$$\tau_{DR}^{*DR} - (\tau_D^{*CD} + \tau_R^{*CD}) = \frac{1}{16} > 0 .$$

Subtracting R's profit under Model CD from that under Model MD, we can get:

$$\tau_R^{*MD} - \tau_R^{*CD} = \frac{3(1+4\lambda)}{16(1+2\lambda)} > 0$$

Subtracting coalition MD's profit under Model MD from the total profit of M and D under Model CD, we obtain

$$\tau_M^{*CD} + \tau_D^{*CD} - \tau_{MD}^{*MD} = -\frac{1-\lambda}{8(1+2\lambda)} .$$

If $0 < \lambda < 1$, $\tau_M^{*CD} + \tau_D^{*CD} - \tau_{MD}^{*MD} = -\frac{1-\lambda}{8(1+2\lambda)} < 0$;

If $\lambda > 1$, $\tau_M^{*CD} + \tau_D^{*CD} - \tau_{MD}^{*MD} = -\frac{1-\lambda}{8(1+2\lambda)} > 0$.

Taking partial derivatives of MD's and R's optimal profits under Model MD with respect to R's fairness concern parameter $\lambda$, we confirm that

$$\frac{\partial \tau_{MD}^{*MD}}{\partial \lambda} = -\frac{1}{2(1+2\lambda)^2} < 0 \text{ and } \frac{\partial \tau_R^{*MD}}{\partial \lambda} = \frac{1}{2(1+2\lambda)^2} > 0 .$$

The proof of Proposition 8 is thus completed.

**Appendix I. Proof of Proposition 9**

Given the equilibrium pricing decisions and sale quantities of the new and remanufactured products under various models, we can calculate their optimal profits as follows:

$$\pi_T^{CC(n)} = (p_n^{*CC} - c_n) \times q_n^{*CC} = \frac{1}{4}\chi ,\ \pi_T^{CC(r)} = (p_r^{*CC} - c_r - A) \times q_r^{*CC} = \frac{1}{4}\gamma ,$$

$$\pi_T^{CD(n)} = (p_n^{*CD} - c_n) \times q_n^{*CD} = \frac{7}{64}\chi ,\ \pi_T^{CD(r)} = (p_r^{*CD} - c_r - A) \times q_r^{*CD} = \frac{7}{64}\gamma ,$$

$$\pi_M^{CD(n)} = (m_n^{*CD} - c_n) \times q_n^{*CD} = \frac{1}{16}\chi ,\ \pi_M^{CD(r)} = (m_r^{*CD} - c_r - A) \times q_r^{*CD} = \frac{1}{16}\gamma ,$$

$$\pi_D^{CD(n)} = (w_n^{*CD} - m_n^{*CD}) \times q_n^{*CD} = \frac{1+\lambda}{32(1+2\lambda)}\chi ,\ \pi_D^{CD(r)} = (w_r^{*CD} - m_r^{*CD}) \times q_r^{*CD} = \frac{1+\lambda}{32(1+2\lambda)}\gamma ,$$

$$\pi_R^{CD(n)} = (p_n^{*CD} - w_n^{*CD}) \times q_n^{*CD} = \frac{1+4\lambda}{64(1+2\lambda)}\chi, \pi_R^{CD(r)} = (p_r^{*CD} - w_r^{*CD}) \times q_r^{*CD} = \frac{1+4\lambda}{64(1+2\lambda)}\gamma,$$

$$\pi_T^{MD(n)} = (p_n^{*MD} - c_n) \times q_n^{*MD} = \frac{3}{16}\chi, \pi_T^{MD(r)} = (p_r^{*MD} - c_r - A) \times q_r^{*MD} = \frac{3}{16}\gamma,$$

$$\pi_{MD}^{MD(n)} = (w_n^{*MD} - c_n) \times q_n^{*MD} = \frac{1+\lambda}{8(1+2\lambda)}\chi, \pi_{MD}^{MD(r)} = (w_r^{*MD} - c_r - A) \times q_r^{*MD} = \frac{1+\lambda}{8(1+2\lambda)}\gamma,$$

$$\pi_R^{MD(n)} = (p_n^{*MD} - w_n^{*MD}) \times q_n^{*MD} = \frac{1+4\lambda}{16(1+2\lambda)}\chi, \pi_R^{MD(r)} = (p_r^{*MD} - w_r^{*MD}) \times q_r^{*MD} = \frac{1+4\lambda}{16(1+2\lambda)}\gamma,$$

$$\pi_T^{DR(n)} = (p_n^{*DR} - c_n) \times q_n^{*DR} = \frac{3}{16}\chi, \pi_T^{DR(r)} = (p_r^{*DR} - c_r - A) \times q_r^{*DR} = \frac{3}{16}\gamma,$$

$$\pi_M^{DR(n)} = (m_n^{*DR} - c_n) \times q_n^{*DR} = \frac{1}{8}\chi, \pi_M^{DR(r)} = (m_r^{*DR} - c_r - A) \times q_r^{*DR} = \frac{1}{8}\gamma,$$

$$\pi_{DR}^{DR(n)} = (p_n^{*DR} - m_n^{*DR}) \times q_n^{*DR} = \frac{1}{16}\chi, \pi_{DR}^{DR(r)} = (p_r^{*DR} - m_r^{*DR}) \times q_r^{*DR} = \frac{1}{16}\gamma,$$

where $\chi = \frac{(1-c_n)(1+A+c_r-\delta-c_n)}{(1-\delta)}$ and $\gamma = \frac{(\delta-A-c_r)(\delta c_n - A - c_r)}{\delta(1-\delta)}$.

Proposition 9(2) can be directly derived from Propositions 1-4.

The proof of Proposition 9 is thus completed.

**Appendix J. Proof of Proposition 10**

By comparing the wholesale prices and optimal profits in the case where $\lambda > 0$ with those in the case where $\lambda = 0$ under Models CD and MD, it is obvious that

$$w_n^{*CD}\Big|_{\lambda>0} - w_n^{*CD}\Big|_{\lambda=0} = -\frac{\lambda(1-c_n)}{4+8\lambda} < 0, \; w_r^{*CD}\Big|_{\lambda>0} - w_r^{*CD}\Big|_{\lambda=0} = -\frac{\lambda(\delta-A-c_r)}{4+8\lambda} < 0,$$

$$w_n^{*MD}\Big|_{\lambda>0} - w_n^{*MD}\Big|_{\lambda=0} = -\frac{\lambda(1-c_n)}{2+4\lambda} < 0, w_r^{*MD}\Big|_{\lambda>0} - w_r^{*MD}\Big|_{\lambda=0} = -\frac{\lambda(\delta-A-c_r)}{2+4\lambda} < 0,$$

$$\pi_D^{*CD}\Big|_{\lambda>0} - \pi_D^{*CD}\Big|_{\lambda=0} = -\frac{\lambda}{8+16\lambda}K < 0, \; \pi_R^{*CD}\Big|_{\lambda>0} - \pi_R^{*CD}\Big|_{\lambda=0} = \frac{\lambda}{8+16\lambda}K > 0,$$

$$\pi_{MD}^{*MD}\Big|_{\lambda>0} - \pi_{MD}^{*MD}\Big|_{\lambda=0} = -\frac{\lambda}{2+4\lambda}K < 0, \; \pi_R^{*MD}\Big|_{\lambda>0} - \pi_R^{*MD}\Big|_{\lambda=0} = \frac{\lambda}{2+4\lambda}K > 0.$$

The proof of Proposition 10 is thus completed.

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**Highlights**

- We study a three-echelon closed-loop supply chain with a fairness-minded retailer.
- Game analyses are conducted to characterize interactions among different parties.
- Three cooperative game coordination mechanisms are used to allocate surplus profit.
- Different coordination mechanisms offer distinct options to supply chain managers.
- We examine the impact of the retailer's fairness concerns on profit allocation.