

# Comparative Modeling of Closed-loop and Circular Economy Supply Chains with Extended Warranties

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## Abstract

**Purpose:** This paper investigates the interaction between a manufacturer's extended warranty design and the choice of closed-loop supply chain (CLSC) and circular economy supply chain (CESC) structures for the collection of used products. **Design/methodology/approach:** We consider two CLSC formats and one CESC format, modeling the resulting three combinational scenarios as decentralized decision-making systems with the manufacturer as the Stackelberg leader. **Findings:** Our results show that, when the manufacturer provides extended warranty services, assigning product recycling responsibility to the retailer leads to the highest profits for the manufacturer, the retailer, and the entire supply chain. **Research limitations/implications:** The study focuses on specific CLSC and CESC structures; future research could extend the model to other supply chain configurations and market conditions. **Practical implications:** The findings provide guidance for manufacturers and retailers on designing extended warranty services and choosing supply chain structures to maximize overall profit. **Originality/value:** This study highlights the combined effect of extended warranties and supply chain structure choice on performance, offering new insights for both closed-loop and circular economy supply chain management. **Keywords:** Supply Chain Management, Circular Economy Supply Chain, Extended Warranty

## Introduction

Natural resource scarcity has emerged as a critical global challenge, threatening sustainable development and energy security while intensifying pressures on supply chain systems (Zhang & Xiao-feng, 2025). Moreover, the prevailing linear production and hyper-consumption patterns continue to accelerate ecological degradation, calling for a transition from resource abundance to responsible scarcity (Ramírez-Márquez et al., 2025). At the same time, the

growing volume of end-of-life products and the increasing importance of reverse logistics highlight the critical role of end-of-life product management in achieving both environmental and economic value (Wilson & Goffnett, 2022). From a circular economy perspective, effective end-of-life management is also contingent on firms' dynamic capabilities, making it essential for sustainable product design and resource recovery (Quaicoe et al., 2024). In response to these challenges, extended producer responsibility (EPR) has been increasingly recognized as a key policy instrument to ensure the proper management of end-of-life products, such as batteries and electronics (Chuang et al., 2024; Chaerul & Indrapta, 2024). From the firm's perspective, sustainability practices are increasingly linked to improved financial outcomes, as companies engaging in corporate social responsibility initiatives often achieve superior performance (Ghardallou, 2022). Moreover, sustainable firm performance is shaped by governance mechanisms such as risk disclosure, underscoring the need for firms to balance sustainability objectives with financial stability (Alsulami, 2024).

Together, these resource, environmental, policy, and performance challenges have motivated the emergence of innovative supply chain models such as Closed-Loop Supply Chains (CLSCs) and Circular Economy Supply Chains (CESCs). These models directly respond to the need to reconcile sustainability objectives with firm performance, aiming to enhance environmental outcomes while maintaining competitiveness. In recent years, Closed-Loop Supply Chains (CLSCs) have gained significant attention as a practical strategy to reduce environmental impact, recover value from used products, and enhance sustainability through remanufacturing and recycling (Zengin et al., 2024). CLSCs are typically characterized by the manufacturer's direct involvement in product take-back, either independently or via retailers, allowing for greater control over product quality and reverse logistics (Zheng & Hong, 2021). However, with the growing emphasis on collaborative sustainability and circularity, the emergence of Circular Economy Supply Chains (CESCs) has introduced a more decentralized and inclusive model (Kurniawan & Fernando, 2023). CESCs often involve third-party entities in the recovery process, enabling broader stakeholder participation and potentially improving the overall efficiency and reach of product return systems (Zarbakhshnia et al., 2022). However, prior studies typically examine CLSC and CESC in isolation, and a unified comparison that embeds reverse collection choices in both settings remains limited (e.g., Savaskan et al., 2004; Zengin et al., 2024; Kurniawan & Fernando, 2023).

Extended warranties have become a prevalent practice in global markets, representing a highly profitable and rapidly expanding business (Bošković et al., 2024). According to Wang et al. (2024), extended warranties are highly profitable after-sales service contracts that consumers can purchase together with durable goods. They are also widely offered on products such as consumer electronics, cars, and household appliances. These warranties are typically sold at high premiums relative to actual product failure rates, and many consumers still buy them despite their negative expected value, particularly when product choices are difficult or emotionally taxing (Montal-Rosenberg et al., 2025). Beyond the consumer perspective, extended warranties also play an essential role in shaping supply chain strategies and outcomes. Liu et al. (2024) show that offering warranty services on retail platforms alters manufacturers' pricing strategies and changes product market structures, underscoring the strategic implications of warranties in competitive environments. From the closed-loop supply chain perspective, Jalapathy and Unnissa (2024) highlight that coordinating warranty lengths and prices between manufacturers and retailers enhances profitability and efficiency,

especially when remanufacturing and trade-in programs are involved. Similarly, Zha et al. (2024) emphasize the importance of integrating extended warranty services into the “product + service” model, showing that quality cost-sharing contracts not only improve supply chain coordination but also support circular economy objectives by extending product lifecycles and enhancing sustainability. Most warranty studies are embedded in closed-loop or single-channel settings, offering little direct comparison with CESC and seldom linking consumer risk aversion with reverse-collection responsibility (e.g., Zhu et al., 2022; Jalapathy & Unnissa, 2024).

Addressing this gap is essential for deriving structure-dependent extended warranty and collection policies with clear managerial relevance. Therefore, this study focuses on comparing closed-loop and circular economy supply chain models by examining how extended warranty strategies interact with reverse channel configurations for used product collection. To explore the impact of reverse channel configurations under extended warranties, we model a two-echelon system comparing closed-loop and circular economy supply chains. The setting involves a manufacturer-retailer dyad where the manufacturer supplies both new and remanufactured products, with no differentiation in quality or market treatment between the two types.

Based on observations from current practice and the extant literature, we consider two CLSC formats (i.e., manufacturer collecting, retailer collecting) and one CESC format (third-party collecting). Thus, there are three decentralized CLSC models with extended warranties, viz., the manufacturer collects used products (Model MM), the retailer collects used products (Model RM), and the third party collects used products (Model TM).

The key contributions of this study can be summarized as follows:

1. We develop a unified analytical framework that compares CLSC and CESC under manufacturer-provided extended warranties.
2. We incorporate consumer risk aversion into a Stackelberg game to reveal how extended warranty design and reverse-channel responsibility jointly shape equilibrium outcomes.
3. We derive actionable implications for assigning collection responsibility and pricing extended warranties.

Building on these contributions, we address two specific research questions:

1. When the manufacturer offers the extended warranty, what are the optimal decisions of CLSC and CESC supply chain members?
2. How do these decisions differ between closed-loop and circular economy supply chain structures?

### **Literature Review**

Prior research has separately examined extended warranties, as well as closed-loop (CLSC) and circular economy (CESC) supply chains in the context of remanufacturing, but largely in isolation. Accordingly, the literature review is organized around three key domains: extended warranties, closed-loop supply chains (CLSCs), and circular economy supply chains (CESCs).

Recent research on extended warranties (EWs) has focused on their design, pricing, and integration into supply chain strategies. Wang et al. (2020) analyze warranty menus with multiple options differing in length and price, using a power-law process to model failures and

a multinomial logit model to capture consumer choice. They show that a cost-plus-margin strategy with equal margins is optimal, while limited menus should prioritize high-valuation options. Building on this work, Wang et al. (2025) incorporate reference effects into consumer valuation, demonstrating that consumers compare warranty choices relative to endogenous and exogenous benchmarks. Their model prescribes consistent markups and alternating price-length ratios, and competition under reference effects yields a unique Nash equilibrium. Together, these studies highlight the central role of consumer heterogeneity and reference-dependent behavior in shaping optimal extended warranty pricing strategies.

From a supply chain perspective, scholars have also examined which party should provide warranties and how warranties interact with reverse logistics. Li et al. (2012) use game-theoretic models to compare manufacturer- and retailer-provided warranties, showing that profitability depends on the provider and that centralized systems improve efficiency, with third-party resale as an alternative mechanism. In online retailing, Zhang et al. (2024) compare provision models and find that manufacturer warranties sustain consumer demand, while dual-provider settings enhance profitability under fixed quality but not under endogenous quality. Extending this analysis to closed-loop contexts, Zhu et al. (2022) demonstrate that dual price sensitivity and remanufacturing cost savings significantly affect outcomes under different channel power structures, and they propose coordinating contracts to improve system performance. Similarly, Zhou et al. (2025) show that warranty response times influence consumer utility and pricing across retail formats, emphasizing the need to balance price and service speed. Finally, Li et al. (2023) evaluate the role of consumption subsidies in shaping extended warranty strategies, finding that retailer warranties improve economic performance, while optimal subsidy design is required to balance profitability, consumer surplus, and environmental goals. Collectively, these studies reveal that extended warranty design is shaped not only by consumer behavior but also by supply chain structures and policy environments, underscoring the importance of integrating warranty strategies into broader supply chain decision-making.

Savaskan et al. (2004) analyze reverse channel design for product collection, comparing manufacturer-, retailer-, and third-party-led systems in a Stackelberg framework. They show that retailers are most effective due to proximity to consumers and that coordination mechanisms can align decentralized and centralized outcomes, providing a theoretical foundation for later CLSC research. Building on this foundation, Li et al. (2025) propose a closed-loop supply chain network optimization model that incorporates corporate social responsibility (CSR), recycling, remanufacturing, refurbishing, and transaction costs. Their results show that CSR improves overall system performance, but downstream actors closer to consumers benefit more significantly. Similarly, Guo et al. (2025) construct a remanufacturing closed-loop supply chain model under uncertain market demand and product quality, using fuzzy programming and meta-heuristic optimization. They find that carbon taxes alone may reduce emissions but substantially raise costs, discouraging firm participation. In contrast, Luo et al. (2022) demonstrate that poorly designed carbon taxes may deter remanufacturing, underscoring the need for tailored, industry-specific policies to balance profitability with emissions reduction. Moreover, research has emphasized coordination mechanisms and innovation strategies to improve CLSC outcomes. Ding et al. (2025) study end-of-life vehicle recovery in supplier-, manufacturer-, and third-party-led modes. They show that supplier-led collection can be optimal when supported by transfer

price and fixed payment contracts, which align recovery rates with centralized outcomes and improve efficiency, though leadership structure may alter optimal channel choice. Extending this line of inquiry, Chai et al. (2024) analyze process innovation in green product remanufacturing using game-theoretic models. They find that cooperative innovation between suppliers and manufacturers enhances supply chain and environmental outcomes but may not appeal to manufacturers alone; government subsidies can incentivize cooperation, leading to improved recovery and sustainability. Finally, Chen et al. (2023) incorporate consumer low-carbon preferences and carbon emission reduction (CER) subsidies into a hybrid recycling closed-loop supply chain model. Their analysis shows that subsidies and preferences increase recycling and profits, while cost–benefit sharing contracts improve coordination, reduce channel competition, and enhance both environmental outcomes and stakeholder performance.

Ghisellini et al. (2016) provide a comprehensive review tracing the origins of the circular economy (CE) to ecological economics and industrial ecology. They emphasize its role in promoting resource efficiency through closed-loop production and waste reduction. The study contrasts China’s top-down policy-driven approach with the European Union’s bottom-up environmental management strategies, highlighting that CE implementation remains at an early stage and requires coordinated efforts from multiple societal actors to decouple growth from environmental pressure. Building on this foundation, Genovese et al. (2017) examine CE practices in the chemical and food industries by comparing them with traditional production models. Using lifecycle indicators such as emissions, waste recovery, and virgin resource use, they demonstrate that circular systems achieve superior environmental outcomes, while also presenting new managerial challenges. Extending this perspective, Cerqueira-Streit et al. (2021) review the integration of sustainable supply chain management and CE, particularly in the post-COVID-19 context, showing how CE reshapes manufacturing, distribution, consumption, and recovery processes. From a theoretical standpoint, Batista et al. (2023) introduce the concept of a “sustainability-dominant logic” that links sustainable operations and supply chain management with CE principles across product, firm, and supply chain levels, providing a unifying lens for future research.

From a technological and practical perspective, recent studies highlight the enablers and performance outcomes of CE adoption. Vaezinejad et al. (2025) conduct a systematic review at the intersection of digital technologies and CE, proposing a three-level micro–meso–macro framework that synthesizes numerous theories and illustrates how tools such as artificial intelligence (AI) and the Internet of Things (IoT) can act as digital enablers of circular practices. Empirical evidence further supports these insights: Sun et al. (2025), analyzing 1,766 Chinese firm-year observations, find a positive relationship between CE practices and firm performance, but also reveal that blockchain adoption can weaken CE benefits in resource-constrained firms, underscoring the importance of contextual factors. Complementing these findings, Bai et al. (2022) develop a circularity assessment framework for supplier evaluation, offering metrics across multiple levels and a hybrid decision-making method that accommodates uncertainty and divergent stakeholder views. Together, these studies demonstrate how technological innovation and methodological advances strengthen the theoretical and practical foundations of CE-oriented supply chain management.

Although prior studies have examined extended warranties in supply chains and explored reverse logistics in closed-loop and circular economy settings, three important gaps remain. First, most works investigate CLSC and CESC separately and rarely offer a unified analytical comparison of their reverse-collection structures (e.g., Zengin et al., 2024; Kurniawan & Fernando, 2023). Second, although many studies analyze extended warranty strategies, they usually examine a single reverse-collection mode and seldom compare how extended warranty design performs across different collection configurations (e.g., Zhu et al., 2022; Jalapathy & Unnissa, 2024). Third, very few studies incorporate consumer risk aversion when examining extended warranty decisions in different reverse-collection modes, leaving the behavioral dimension underexplored.

To fill these gaps, this study develops a unified framework that compares CLSC and CESC under manufacturer-provided extended warranties, integrates consumer risk aversion into a Stackelberg game model, and derives managerial insights for assigning collection responsibility and pricing extended warranties.

### *Hypothesis Development*

Given that this study is based on an analytical modeling framework rather than an empirical analysis, this section presents the model assumptions and notation that underpin the development of subsequent propositions. We consider a simple supply chain consisting of a manufacturer and an independent retailer. Assume that the manufacturer has incorporated a remanufacturing process for used products into her original production system, so that she can manufacture a new product directly from raw materials, or remanufacture part or whole of a returned unit into a new product. The unit cost of manufacturing a new product is  $c_m$ , and the unit cost of remanufacturing a returned product into a new one is  $c_r$ . Assume that  $c_r < c_m$  and we denote unit cost savings from remanufacturing by  $\Delta$ , i.e.,  $\Delta = c_m - c_r$ . There is no distinction between a remanufactured and a manufactured product (Savaskan et al., 2004). The manufacturer sells the product exclusively through the retailer at a wholesale price  $w$ , and the retailer resells it to customers at a retail price  $p$ . Additionally, we use the following notation throughout the paper:  $A$  denotes the variable unit cost of collecting and handling a returned product from the consumer, and  $B$  denotes the unit transfer price of a returned product from the retailer/third party to the manufacturer. For remanufacturing to be economically viable, we assume that  $A < \Delta$ .  $D_1$  is the demand for the product, and  $D_2$  is the demand for the extended warranty.  $\pi_h^{ij}$  denotes the profit function for a channel member  $h$  in the supply chain model  $ij$ . Superscript  $i$  will take values  $M$ ,  $R$ , and  $T$ , which denote the manufacturer collecting, the retailer collecting, and the third-party collecting models, respectively. Superscript  $j$  will take values  $M$ , which denote the manufacturer offering the extended warranty. The subscript  $h$  will take values  $M$ ,  $R$ ,  $T$  and  $SC$ , which denote the manufacturer, the retailer, the third party, and the total supply chain, respectively.

The manufacturer provides the original product warranty, whose length is normalized to zero. This assumption enables us to focus exclusively on the analysis of the extended warranty (Li et al., 2012). Following Desai and Padmanabhan (2004), this study assumes that the product provides the consumer with a monetary utility of  $\theta$ , and the consumer incurs a loss of  $\delta$  when the product fails. Let  $\delta$  be a random variable, and the retail price of the product be  $p$

. For a given  $\delta$ , the consumer's net utility from purchasing the product is  $\theta - p - \delta$ . Define the expected monetary loss as  $\bar{\delta}$ , then the expected utility from purchasing the product is  $\theta - p - \bar{\delta}$ . Assume that the consumer makes two sequential decisions: whether to purchase the product, and if so, whether to purchase the extended warranty service. The price of the extended warranty is denoted as  $p_e$ . If the product fails during the warranty period, the extended warranty compensates the consumer an amount of  $(1 - \alpha)\delta$ , where  $0 \leq \alpha \leq 1$ . The average warranty cost per product is then  $n = (1 - \alpha)\bar{\delta}$ . Therefore, the consumer's actual loss upon product failure when having purchased the extended warranty is  $\alpha\delta$ . The consumer's expected utility from purchasing both the product and the extended warranty is thus  $\theta - p - p_e - \alpha\bar{\delta}$ . To capture heterogeneity in consumer risk preferences, we assume the consumer's risk aversion coefficient  $r$  is uniformly distributed over the interval  $(0, 1)$ .

The risk aversion perspective on extended warranties proposed by Padmanabhan and Rao (1993) suggests that only risk-averse consumers are inclined to purchase extended warranty products. In the context of this chapter's discussion on risk aversion, if  $r_2 > r_{12}$ , then consumers with a risk aversion coefficient of  $r_2$  are more risk-averse than those with  $r_{12}$  (see Figure 1).

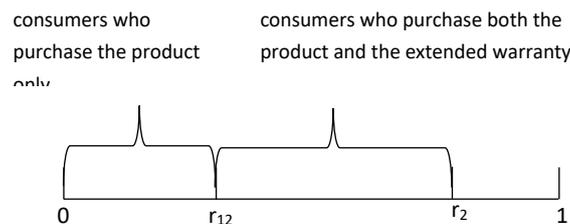


Figure 1. Distribution of Consumer Risk Aversion

This naturally translates into consumers' demand for extended warranty services. When  $U_1 = U_2$  these consumers are indifferent between purchasing the product alone and purchasing both the product and the extended warranty. According to the certainty equivalence principle, this condition can be expressed as:

$$\theta - p - \bar{\delta} - \frac{r}{2}\sigma^2 = \theta - p - p_e - \alpha\bar{\delta} - \frac{r}{2}\alpha^2\sigma^2$$

Here,  $\bar{\delta}$  and  $\sigma^2$  represent the mean and variance of  $\delta$ , respectively. It follows that:

$$r_{12} = \frac{2[p_e - (1 - \alpha)\bar{\delta}]}{\sigma^2(1 - \alpha^2)}$$

All consumers with a risk aversion level  $r < r_{12}$  will find that purchasing the product alone is the optimal choice. To derive the demand for the extended warranty, we observe that for some marginal consumers, the utility from simultaneously purchasing the product and the extended warranty is equal to the utility from purchasing nothing—both yielding zero monetary utility. That is  $U_2 = U_0 = 0$ . Applying the certainty equivalence model, we obtain:

$$\theta - p - p_e - \alpha\bar{\delta} - \frac{r}{2}\alpha^2\sigma^2 = 0$$

Therefore:

$$r_2 = \frac{2[\theta - p - p_e - \alpha\bar{\delta}]}{\sigma^2\alpha^2}$$

All consumers with a risk aversion level  $r > r_2$  will find that not purchasing the product is the optimal choice (including the extended warranty, of course). The resulting demand for the product is given by:

$$D_1 = r_2 = k_1(\theta - \alpha\bar{\delta} - p - p_e)$$

Where  $k_1 = \frac{2}{\alpha^2\sigma^2}$ .

$s_1$  and  $s_2$  represent the selling costs associated with the product and the extended warranty, respectively. This reflects a typical feature of durable goods marketing systems, where the sales process often involves significant interaction between consumers and sales agents. The time cost of such sales efforts is typically borne by the firm and is assumed to be constant, regardless of who is responsible for selling the product to the consumer. In other words, the selling cost related to the extended warranty is assumed to be the same, whether the manufacturer sells directly to consumers or the retailer sells the extended warranty to consumers. The complete set of parameters is summarized in Table 1.

Table 1

*Model Parameters and Corresponding Definitions*

Parameter	Definition
$\theta$	Monetary utility of the product
$\delta$	Consumer loss when the product fails
$c_m$	Unit production cost of the product
$c_r$	Unit production cost of the remanufactured product
$\Delta$	Unit cost savings from remanufacturing
$A$	Unit cost of product collection and processing
$n$	Unit cost of extended warranty provision
$c_l$	Cost scale parameter for collection
$s_1$	Unit selling cost of the product
$s_2$	Unit selling cost of the extended warranty
$r$	Consumer risk aversion coefficient
Decision Variables	
$w$	Wholesale price of the product
$p$	Retail price of the product
$\tau$	Product return rate
$p_e$	Extended warranty price
$B$	Unit transfer payment (from manufacturer to collector)

Following Savaskan et al. (2004) and Desai and Padmanabhan (2004), this paper also adopts the following assumptions:

(1) The product return rate  $\tau$  is a function of the collection effort  $I$ , given by  $\tau = \sqrt{I/c_l}$ , where  $c_l$  is the cost scale parameter. The total collection cost is defined as  $c(\tau) = I + A\tau D_1 = c_l\tau^2 + A\tau D_1$ .

- (2) The consumer risk aversion coefficient  $r$  is uniformly distributed over the interval (0,1).
- (3) A single-period static supply chain decision is considered, and full information symmetry is assumed within the supply chain.
- (4) The manufacturer possesses sufficient channel power and acts as the leader in the Stackelberg game.

(5) Let  $c_m + s_1 + \delta + \frac{2k_2s_2}{\alpha^2k_1} < \theta < c_m + s_1 + s_2 + \delta + \frac{2}{k_1}$  (Condition (I)) and

$$c_l > \max \left\{ \frac{k_1(A-\Delta)^2}{4+k_1(c_m+s_1+s_2+\bar{\delta}-\theta)}, \frac{k_1(A-\Delta)^2+k_1(A-\Delta)(c_m+s_1+s_2+\bar{\delta}-\theta)}{4} \right\} \text{ (Condition (II))}$$

(II)), to ensure that the demands for both the product and the extended warranty are positive.

**Methods**

This section develops the analytical framework used to evaluate closed-loop and circular economy supply chains under extended warranty provision. Based on the model assumptions introduced in the previous section, we present four decision-making structures—one centralized benchmark and three decentralized Stackelberg game models—and derive their equilibrium outcomes.

*Model C—Centrally Coordinated System*

The Centrally coordinated system (Model C, see Figure 2a) provides a benchmark scenario to compare the decentralized models concerning the supply chain profits and the optimal decisions. Because there is a single decision maker, the wholesale price  $w$  and the transfer price  $B$  are irrelevant to the formulation of the objective function. Hence, the central planner optimizes

$$\text{Max}_{p,p_e,\tau} \pi^C = (p - c_m - s_1)D_1 + (p_e - n - s_2)D_2 + (\Delta - A)\tau D_1 - c_l\tau^2$$

The Hessian matrix of the objective function is given as follows:

$$H = \begin{bmatrix} -2k_1 & -2k_1 & k_1(A-\Delta) \\ -2k_1 & -2(k_1+k_2) & k_1(A-\Delta) \\ k_1(A-\Delta) & k_1(A-\Delta) & -2c_l \end{bmatrix}$$

When the Hessian matrix is negative definite, i.e., Condition (II) is satisfied, the problem admits the following optimal solution:

$$p^{*C} = \frac{1}{2} \left( 2\theta - 2\bar{\delta} - s_2 + \frac{4c_l(-\theta + \bar{\delta} + c_m + s_1 + s_2)}{4c_l - k_1(A-\Delta)^2} \right)$$

$$\tau^{*C} = \frac{k_1(\theta - \bar{\delta} - c_m - s_1 - s_2)(A-\Delta)}{-4c_l + k_1(A-\Delta)^2}$$

$$\pi_{SC}^{*C} = \frac{1}{4}k_2s_2^2 + \frac{c_l k_1(-\theta + \bar{\delta} + c_m + s_1 + s_2)^2}{4c_l - k_1(A-\Delta)^2}$$

*Manufacturer Offers Extended Warranty*

In this section, we introduce two CLSC models and one CESC model, where the manufacturer collects used products directly (model MM, see Figure 2b), the retailer collects used products

(Model RM, see Figure 2c), or the third party collects used products (model TM, see Figure 2d). In all these models, the manufacturer offers the extended warranty directly to the consumers and incurs all associated costs. We are mostly interested in comparing these models in terms of the optimal supply chain decisions and the system profit.

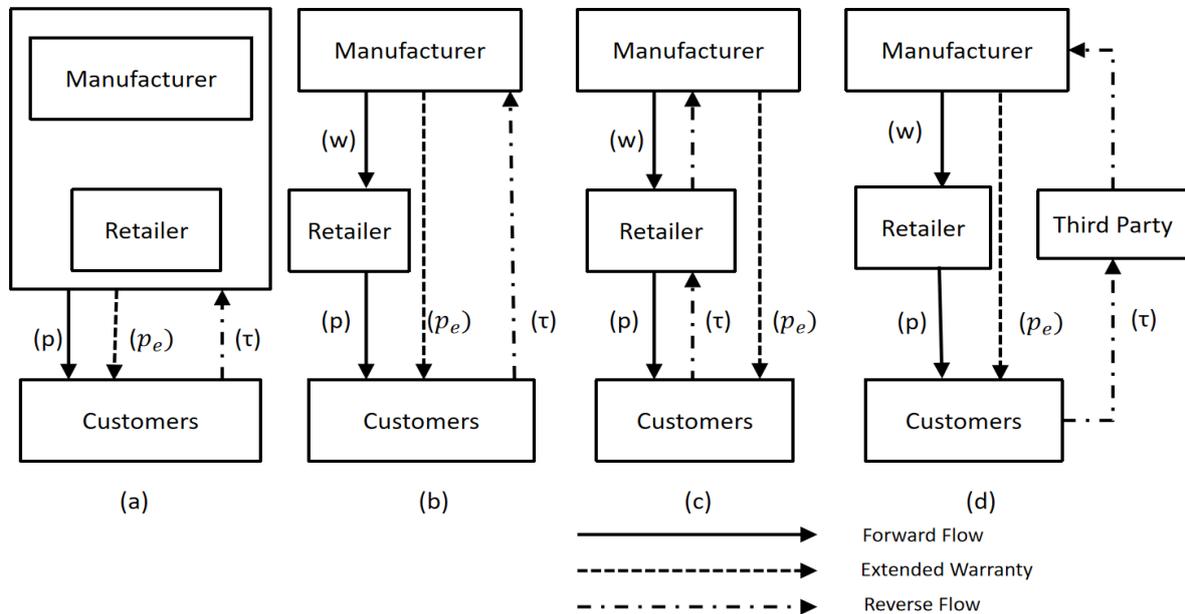


Figure 2. CLSC and CESC models with the manufacturer provide extended warranties

In Model MM, the manufacturer collects used products directly and provides the extended warranty service. In this Stackelberg game, the manufacturer acts as the leader and first determines the wholesale price  $w$ , the product return rate  $\tau$ , and the extended warranty price  $p_e$ . The manufacturer’s profit function is as follows:

$$\text{Max}_{w,p_e,\tau} \pi_M^{MM} = (w - c_m)D_1 + (p_e - n - s_2)D_2 + (\Delta - A)\tau D_1 - c_t \tau^2$$

Given the wholesale price, the retailer determines the retail price  $p$  to maximize its profit.

The retailer’s profit function is as follows:

$$\text{Max}_p \pi_R^{MM} = (p - w - s_1)D_1$$

By applying backward induction to solve the above problem, the retailer’s optimal response

function is  $p^{*MM} = \frac{1}{2}(\theta - \alpha \bar{\delta} + s_1 - p_e + w)$ , Substituting this into the manufacturer’s profit

function, we can derive the optimal wholesale price, return rate, and extended warranty price. Then, by substituting them into the retailer’s profit function, the retailer’s maximum profit can be obtained.

In Model RM, the retailer is responsible for collecting used products, while the manufacturer provides the extended warranty service. First, the manufacturer decides on the wholesale price  $w$ , the transfer payment  $B$ , and the extended warranty price  $p_e$ . The manufacturer’s profit function is as follows:

$$\text{Max}_{w,B,p_e} \pi_M^{RM} = (w - c_m)D_1 + (p_e - n - s_2)D_2 + (\Delta - B)\tau D_1$$

Afterwards, the retailer decides on the retail price  $p$  and the product return rate  $\tau$ . The retailer's profit function is as follows:

$$\text{Max}_{p,\tau} \pi_R^{RM} = (p - w - s_1)D_1 + (B - A)\tau D_1 - c_l \tau^2$$

By applying backward induction, the retailer's optimal decisions are obtained as follows:

$$p^{*RM} = \frac{2c_l(\theta - \alpha\bar{\delta}) + k_1(p_e - \theta - \alpha\bar{\delta})(A - B)^2}{4c_l - k_1(A - B)^2} \quad \tau^{*RM} = \frac{(B - A)k_1(\theta - \alpha\bar{\delta} - s_1 - p_e - w)}{4c_l - k_1(A - B)^2}$$

Substituting these into the manufacturer's profit function, the manufacturer's optimal decisions  $w^{*RM}$  and  $p_e^{*RM}$  can be obtained. The manufacturer's profit function is:

$$\frac{1}{4}(k_2 s_2^2 + \frac{2c_l k_1(\theta - \bar{\delta} - c_m - s_1 - s_2)^2}{4c_l - k_1(A - B)(A - \Delta)})$$

The first-order partial derivative of this function with respect to  $B$  is:

$$\frac{c_l k_1^2(\theta - \bar{\delta} - c_m - s_1 - s_2)^2(\Delta - A)}{2(4c_l - k_1(A - B)(A - \Delta))^2}$$

Since  $\Delta - A > 0$  the derivative is always positive, which means the function value increases with  $B$ . Moreover, since  $B \leq \Delta$ , the manufacturer's profit reaches its maximum when  $B = \Delta$ . At this point, all the revenue from remanufacturing is obtained by the recycler.

In the TM model, a third party is responsible for collecting used products, while the manufacturer provides the extended warranty. First, the manufacturer decides on the wholesale price  $w$ , the transfer payment price  $B$ , and the extended warranty price  $P_e$ . The manufacturer's profit function is as follows:

$$\text{Max}_{w,B,p_e} \pi_M^{TM} = (w - c_m)D_1 + (p_e - n - s_2)D_2 + (\Delta - B)\tau D_1$$

Then, the retailer determines the retail price  $p$  of the product. The retailer's profit function is as follows:

$$\text{Max}_p \pi_R^{TM} = (p - w - s_1)D_1$$

The third party determines the product return rate  $\tau$ . The profit function is as follows:

$$\text{Max}_\tau \pi_T^{TM} = (B - A)\tau D_1 - c_l \tau^2$$

By using backward induction, the optimal decision of the third party can be derived as

$$\tau^{*TM} = \frac{(B - A)k_1(\theta - \alpha\bar{\delta} - p - p_e)}{2c_l}, \quad \text{and the retailer's optimal decision is}$$

$$p^{*TM} = \frac{1}{2}(\theta - \alpha\bar{\delta} + s_1 - p_e + w).$$

Substituting  $\tau^{*TM}$  and  $p^{*TM}$  into the manufacturer's profit function, the manufacturer's optimal decisions  $w^{*TM}$  and  $p_e^{*TM}$  can be obtained. The manufacturer's profit function is as follows:

$$\frac{1}{4}(k_2 s_2^2 + \frac{2c_l k_1(-\theta + \bar{\delta} + c_m + s_1 + s_2)^2}{4c_l - k_1(A - B)(B - \Delta)})$$

It can be concluded that when  $B = \frac{A + \Delta}{2}$ , the manufacturer's profit reaches its maximum. At

this point, both the manufacturer and the recycler can obtain the same benefit from remanufacturing. Table 2 presents the optimal decisions and profits of the above three models.

Table 2

*Optimal Decisions and Profits under Models MM, RM, and TM*

Optimal Decisions and Profits	Model MM	Model RM	Model TM
$w^*$	$\theta - \bar{\delta} - s_1 - \frac{1}{2}s_2 + \frac{4c_l R}{8c_l - k_1(A-\Delta)^2}$	$\frac{1}{2}(\theta - \bar{\delta} + c_m - s_1)$	$\theta - \bar{\delta} - s_1 - \frac{1}{2}s_2 + \frac{8c_l R}{16c_l - k_1(A-\Delta)^2}$
$p^*$	$\theta - \bar{\delta} - \frac{1}{2}s_2 + \frac{2c_l R}{8c_l - k_1(A-\Delta)^2}$	$\frac{1}{2}(2\theta - 2\bar{\delta} - s_2) + \frac{c_l R}{4c_l - k_1(A-\Delta)^2}$	$\theta - \bar{\delta} - \frac{1}{2}s_2 + \frac{4c_l R}{16c_l - k_1(A-\Delta)^2}$
$p_e^*$	$\frac{s_2}{2} + \bar{\delta} - \alpha\bar{\delta}$	$\frac{s_2}{2} + \bar{\delta} - \alpha\bar{\delta}$	$\frac{s_2}{2} + \bar{\delta} - \alpha\bar{\delta}$
$\tau^*$	$\frac{k_1 R(\Delta - A)}{-8c_l + k_1(A-\Delta)^2}$	$\frac{k_1 R(A-\Delta)}{8c_l - 2k_1(A-\Delta)^2}$	$\frac{k_1 R(\Delta - A)}{-16c_l + k_1(A-\Delta)^2}$
$\pi_M^*$	$\frac{1}{4}k_2 s_2^2 + \frac{c_l k_1 R^2}{8c_l - k_1(A-\Delta)^2}$	$\frac{1}{4}\left(k_2 s_2^2 + \frac{2c_l k_1 R^2}{4c_l - k_1(A-\Delta)^2}\right)$	$\frac{1}{4}k_2 s_2^2 + \frac{2c_l k_1 R^2}{16c_l - k_1(A-\Delta)^2}$
$\pi_R^*$	$\frac{4c_l^2 k_1 R^2}{(-8c_l + k_1(A-\Delta)^2)^2}$	$\frac{c_l k_1 R^2}{4(4c_l - k_1(A-\Delta)^2)}$	$\frac{16c_l^2 k_1 R^2}{(-16c_l + k_1(A-\Delta)^2)^2}$
$\pi_T^*$	/	/	$\frac{c_l k_1^2 R^2 (A-\Delta)^2}{(-16c_l + k_1(A-\Delta)^2)^2}$
$\pi_{SC}^*$	$\pi_M^{*MM} + \pi_R^{*MM}$	$\frac{1}{4}\left(k_2 s_2^2 + \frac{3c_l k_1 R^2}{4c_l - k_1(A-\Delta)^2}\right)$	$\pi_M^{*TM} + \pi_R^{*TM} + \pi_T^{*TM}$

Note: In the table,  $R = -\theta + \bar{\delta} + c_m + s_1 + s_2$ .

**Findings**

This section summarizes the core findings derived from the analytical results and model comparisons across different collection and extended warranty scenarios.

Based on the summarized results in Table 2, some meaningful insights can be drawn regarding the CLSC and CESC decisions under consumer risk aversion and extended warranty services. Accordingly, the following proposition is presented.

**Proposition 1.** Under consumer risk aversion, when the manufacturer provides extended warranty services, the optimal decisions among the decentralized decision-making models and the centralized model satisfy the following relationships:  $w^{*RM} > w^{*TM} > w^{*MM}$ ,  $\tau^{*C} > \tau^{*RM} > \tau^{*MM} > \tau^{*TM}$ ,  $p^{*TM} > p^{*MM} > p^{*RM} > p^{*C}$ ,  $p_e^{*C} = p_e^{*MM} = p_e^{*RM} = p_e^{*TM}$ .

This proposition shows that under consumer risk aversion, the product return rate is highest and the retail price is lowest in the centralized decision-making model. When the manufacturer provides extended warranty services, the product return rate is lowest in the third-party recycling model(CESC), while the retailer's recycling rate is highest(CLSC). Additionally, the wholesale price is highest in the retailer recycling model and lowest in the manufacturer recycling model, while the retail price is highest in the third-party recycling model (CESC)and lowest in the retailer recycling model(CLSC). Moreover, the optimal extended warranty prices are the same under different recycling channels, indicating that the price of the extended warranty is independent of the recycling channel.

Proposition 2. When the manufacturer provides extended warranty services, there exist the following relationships among the optimal profits under decentralized and centralized decision-making models:  $\pi_M^{*RM} > \pi_M^{*MM} > \pi_M^{*TM}$  ,  $\pi_R^{*RM} > \pi_R^{*MM} > \pi_R^{*TM}$  ,  $\pi^{*C} > \pi_{SC}^{*RM} > \pi_{SC}^{*MM} > \pi_{SC}^{*TM}$  .

This proposition indicates that the centralized decision-making model yields the highest profit for the supply chain. When the manufacturer provides extended warranty services, assigning product recycling responsibility to the retailer leads to the highest profits for the manufacturer, the retailer, and the entire supply chain. This is because the retailer is closer to the market and can directly influence product demand through retail pricing decisions. Under retailer-led recycling, the product retail price is the lowest, resulting in the highest demand. Consequently, the manufacturer can increase profit by selling more products, which also boosts the potential demand for extended warranty services and further enhances the overall system profit.

### Discussion and Conclusion

This section provides a focused discussion of the analytical results in relation to the research questions introduced in Section 1 and developed through the models in Sections 3 and 4. It addresses two central issues: the optimal decisions of supply chain members when the manufacturer provides extended warranties, and the differences in these decisions between closed-loop and circular economy supply chain structures. By linking the theoretical propositions to the study objectives, the analysis highlights how extended warranty design, consumer risk aversion, and responsibility allocation jointly shape equilibrium outcomes and clarifies their broader implications for supply chain coordination, strategic choice of structure, and the advancement of circular economy practices.

The results show the optimal decisions of CLSC and CESC supply chain members under three collection structures—Model MM (manufacturer collection), Model RM (retailer collection), and Model TM (third-party collection). Product wholesale and retail prices, extended warranty price, return rate, and profits are affected by a combination of consumer utility, failure loss, production and selling costs, collection–remanufacturing conditions, and extended warranty selling cost. Specifically:

**Model MM (manufacturer collection):** The manufacturer takes responsibility for collection and provides the extended warranty. The extended warranty price increases with its unit selling cost and decreases with higher consumer risk sharing. Return rates and profits reflect the balance between remanufacturing savings and collection costs.

**Model RM (retailer collection):** The retailer undertakes collection, while the manufacturer remains responsible for the extended warranty. Wholesale and retail prices are influenced by consumer demand, costs, and extended warranty considerations. Profits are jointly generated from product and warranty revenues, amplified by remanufacturing benefits.

**Model TM (third-party collection, CESC):** A third-party handles collection, and the manufacturer provides the extended warranty. Product pricing and return rates are determined by demand, production and selling costs, and the collection–remanufacturing environment. Profits reflect product and warranty revenues combined with remanufacturing savings.

Across the three structures, the extended warranty price is independent of the allocation of collection responsibilities. Distinct patterns emerge in pricing, return rates, and profitability: the wholesale price is highest under retailer collection and lowest under manufacturer collection, while retail prices follow the opposite pattern. Centralized CLSC structures achieve higher return rates, with the CESC structure achieving the lowest due to weaker coordination incentives. Profitability is also highest under retailer-led CLSC, intermediate under manufacturer-led CLSC, and lowest under CESC. These findings highlight the importance of integrating collection responsibilities with extended warranty strategies to enhance both economic and environmental outcomes.

Overall, this study develops a comparative analytical framework for evaluating the performance of closed-loop and circular economy supply chains under consumer risk aversion and extended warranty policies. Assigning collection responsibilities to the retailer improves the profits of all supply chain members and strengthens the alignment between sales and collection activities. This research addresses gaps in the existing literature, which often studies warranty decisions and supply chain structures separately, and provides practical guidance for firms in designing warranty strategies and choosing supply chain structures that maximize profits while supporting sustainable practices.

### **Theoretical Implications**

Across the three structures, the extended warranty price consistently increases with the extended warranty selling cost and decreases with the consumer's risk-sharing ratio. Product pricing is shaped by monetary utility, consumer loss, production and selling costs, and the collection–remanufacturing environment. The return rate is primarily governed by the balance between remanufacturing savings and collection costs, while profits reflect the combined effects of product sales, extended warranty revenues, and remanufacturing savings. These findings underscore the central role of extended warranties in linking consumer expectations with collection activities. Furthermore, comparing the optimal decisions across closed-loop supply chains (CLSC, including Models MM and RM) and the circular economy supply chain (CESC, represented by Model TM) highlights systematic differences in pricing, return rates, and profitability. These results provide new theoretical insights into the interaction among warranty strategies, collection responsibilities, and the design of circular economy supply chains, especially under consumer risk aversion.

### **Practical and Social Implications**

From a managerial perspective, firms should carefully consider the balance between extended warranty pricing, product costs, and collection efficiency, as these jointly determine not only profitability but also consumer participation in product collection. For manufacturers, extended warranties should be coordinated with the allocation of collection responsibility to maximize profits. For retailers, taking on collection responsibilities not only enhances overall supply chain performance but also increases their own profits. From a policy perspective, supporting CLSC arrangements may accelerate the transition toward sustainable production and consumption more effectively than relying on third-party collection under CESC. Governments may adopt incentive and regulatory mechanisms to promote effective cooperation between manufacturers and retailers in warranty and collection activities,

thereby improving recovery rates and advancing the implementation of circular economy supply chains.

### Limitations and Suggestions for Future Research

This study nonetheless has limitations. It is based on a single-manufacturer and single-period game model, which may not fully capture the complexity of competitive markets and dynamic environments. Future research could extend the framework to duopolistic or multi-period settings to examine how extended warranty strategies and collection responsibilities evolve. Moreover, this study focuses only on consumer risk aversion as a behavioral dimension; incorporating additional factors such as environmental awareness, fairness preferences, or bounded rationality would provide a more comprehensive understanding of decision-making in sustainable supply chains.

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