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# Decision and coordination of WEEE closed-loop supply chain with risk aversion under the cap-and-trade regulation

Fuli Zhou[a,*], Chenchen Zhang[a], Sunil Tiwari[b], Xingjun Huang[c], Saurabh Pratap[d]

[a] College of Economics and Management, Zhengzhou University of Light Industry, Zhengzhou, China
[b] University of Bristol Business School, University of Bristol, Howard House, BS8 1SD, Bristol, United Kingdom
[c] School of Modern Posts, Chongqing University of Posts and Telecommunications, Chongqing, China
[d] Department of Mechanical Engineering, Indian Institute of Technology (BHU), Varanasi, U.P, India

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ABSTRACT

Driven by the soaring consumption of electrical and electronic equipment (EEE), the semiconductor industry is facing sustainable development challenges such as energy management and carbon emissions. The waste electrical and electronic equipment (WEEE) management practice could contribute to achieving sustainability in the semiconductor industry through the remanufacturing business. Considering the collection quality heterogeneity and its potential influences on the WEEE remanufacturing process, this paper tries to explore the decision-making strategy and coordination mechanism of the WEEE closed-loop supply chain (CLSC) under the cap-and-trade regulation (CATR). The Stackelberg game model is formulated to address this context consisting of a manufacturer with risk avoidance and a retailer with risk neutrality. Besides, we disclose the specific influence of WEEE collection quality on the strategic decision-making of CLSC members under decentralized and centralized modes. Additionally, the revenue and cost-sharing contract is designed to facilitate coordination within the CLSC, and numerical experiments are performed to help better understand the strategic decision-making and effectiveness of the designed contract mechanism. Results show that within a certain threshold of WEEE collection quality, both recycling rate and total profit increase as collection quality improves, while unit wholesale and retail prices of EEE decrease. Conversely, as the risk aversion of the manufacturer increases, the return rate of WEEE decreases, while the wholesale price and retail price per unit of EEE rise. Under the joint influence of the unit carbon emission quota trading price and risk aversion, the unit carbon emission quota trading price exacerbates the impact of manufacturer risk aversion on the return rate. The revenue and cost-sharing contract also contributes to achieving WEEE CLSC coordination under specific conditions.

## 1. Introduction

The swift progression in manufacturing industries has led to a pronounced escalation in carbon emissions, exacerbating environmental challenges like the greenhouse effect and melting glaciers. To curb carbon emissions, numerous countries have implemented diverse policies. Acknowledged for its operational adaptability, the cap-and-trade regulation (CATR) stands out as a crucial measure in managing carbon emissions (Shi et al., 2023). Under the CATR, companies can trade carbon emissions quotas through the market mechanism, incentivizing voluntary reductions in emissions for additional benefits (Wang et al., 2018b). However, the launch and implementation of this regulation propel enterprises into a more intricate and dynamic decision-making environment. Challenges such as fluctuating carbon trading prices and a lack of experience, compel companies to confront substantial hurdles in production and carbon emission reduction strategies (Shang et al., 2020). Therefore, how companies navigate carbon emissions mitigation while balancing economic viability is a critical research issue actively being explored by many industries, particularly the manufacturing industry.

The rapid pace of technological innovation has driven the iteration of electronic products, resulting in a surge of obsolete products. Consequently, an unprecedented volume of waste electrical and electronic equipment (WEEE) has been generated (Esenduran et al., 2020). Global

* Corresponding author.
*E-mail addresses:* deepbreath329@outlook.com (F. Zhou), zcc19982021@163.com (C. Zhang), sunil.tiwari@bristol.ac.uk (S. Tiwari), xjhuang@cqupt.edu.cn (X. Huang), s.pratapiitkgp@gmail.com (S. Pratap).

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WEEE generation increased by 23.6 metric tons from 2010 to 2020 and is expected to rise to 74.7 metric tons by 2030, making it the fastest-growing solid waste stream in the world (Islam and Huda, 2018). In end-of-life (EOL) products like laptops and mobile phones, the majority of components are semiconductor devices, with exceptions such as screens, batteries, and casings. Semiconductors, which are extensively utilized materials in manufacturing, play crucial roles in integrated circuits, consumer electronics, and mobile communications (Li et al., 2023b). Their production involves intricate processes that require high-temperature furnaces and clean rooms, resulting in high carbon emissions (Yin et al., 2020). Additionally, semiconductor manufacturing requires significant water usage and relies on natural resources such as cobalt, lithium, and gold. It also involves various hazardous chemicals, including perfluorocarbons, posing challenges to climate and natural resource conservation efforts (Sovacool et al., 2021). The reduction of semiconductor material consumption and the effective management of WEEE represent sustainability challenges for countries worldwide.

A device reaching EOL status does not imply that all components are rendered unusable (Zhou et al., 2022). Electrical and electronic equipment (EEE) is a complex entity consisted of thousands of components. Chips, cameras, and various sensors recovered from EOL mobile phones can often be repaired and reused. In 2019 alone, the value of raw materials recovered from WEEE was equivalent to US$57 billion, while the recycling of aluminum, iron, and copper reduced 15 metric tons of carbon emissions (Bressanelli et al., 2020). Emerge as pivotal strategies for companies to manage WEEE, recycling and remanufacturing involve retrieving EOL products, cleaning, repairing, and reprocessing them to ensure they attain the same quality and performance as new items (Agrawal et al., 2015). This approach fosters the establishment of a closed-loop supply chain (CLSC) that operates in a cyclic operational sequence of "products - EOL products - remanufactured products" (Nadar et al., 2021). By harmonizing economic gains with low carbon emissions, the CLSC facilitates the transition of production methods towards a low-carbon paradigm and fosters sustainable development of WEEE (Zhou et al., 2021, 2023b). For example, Apple has reduced the carbon footprint of the MacBook Air and Mac Mini by half through its recycling and remanufacturing initiatives (Roemer et al., 2023). Previous literature has predominantly concentrated on the decision-making of CLSC from the perspectives of WEEE supply chain structure, consumer behavior, and recycling policies (Bui et al., 2021; Tseng et al., 2022). Wang et al. (2020) devised a tripartite evolutionary game model to study the impact of changes in government, recyclers, and consumer behavior on the WEEE recycling industry. Zhang et al. (2021) investigated the effects of government funding policies on the profits of CLSC members and remanufacturing models. However, these studies primarily assume the quality of WEEE is determined, ignoring the impact of factors related to quality heterogeneity on CLSC decision-making.

In practice, variations in consumer usage habits and repair frequency result in differing degrees of damage and degradation among WEEE components, creating significant quality uncertainty (Zhou et al., 2023a). Additionally, the inherent quality differences among various equipment and their respective usage histories add to the quality heterogeneity of WEEE (Islam and Huda, 2018). The heterogeneity quality introduces differences in remanufacturing processes, which contribute to uncertainty in carbon emissions. Moreover, this variation causes fluctuations in the collection quantity, remanufacturing costs, and profits, further increasing the complexity to CLSC operation and management decisions. Consequently, manufacturers tend to make cautious decisions and prioritize risk avoidance to minimize losses during the decision-making process (Simonetto et al., 2022). Within the CLSC, each member primarily focuses on maximizing their marginal benefits while neglecting the revenue impacts on other participants, leading to a phenomenon known as "double marginalization" (Majumder and Srinivasan, 2006). This lack of coordination in decisions frequently drives final price above the optimal level for both manufacturers and retailers, culminating in a lose-lose situation for all involved parties and posing significant challenges to the successful implementation of WEEE remanufacturing activities (De Giovanni and Zaccour, 2022).

Given this, we pose the following questions regarding the WEEE recycling and remanufacturing process.

(1) Faced with the impact of WEEE quality heterogeneity on carbon emissions, recycling costs, and remanufacturing costs, how do manufacturers perform strategic decision-making under the CATR?
(2) How does the risk aversion attitude of manufacturers influence the pricing and profits of CLSC members in the face of uncertainty regarding carbon emissions?
(3) Revenue and cost-sharing contract (RCSC) is an effective coordination mechanism. Can the implementation of RCSC effectively improve the operational efficiency of the supply chain?

To address the above questions, a game model containing a risk-averse manufacturer and a risk-neutral retailer is established. We employ the mean-variance approach, which has been widely used to examine the effects of risk aversion on supply chain operational decisions (Bai et al., 2020; Chiu and Choi, 2016; Choi et al., 2019), to explore the impact of manufacturer's risk aversion and WEEE recycling quality on optimal decision-making. Additionally, to enhance the profits of the manufacturer and retailer under a decentralized model, we advocate for the implementation of an RCSC. This contractual arrangement entails the retailer sharing not only the manufacturer's sales revenue but also carbon trading costs and losses stemming from the manufacturer's risk aversion, aiming to facilitate more rational decision-making for the manufacturer and foster the efficacy of CLSC operations. By considering these factors, this study endeavors to make a significant contribution to the field of supply chain management by enhancing our understanding of decision-making within CLSC, particularly amidst the challenges posed by environmental regulations and market uncertainties.

The main contributions of this study are as follows. Firstly, we simultaneously consider the joint impact of quality heterogeneity and risk aversion on the decision-making of CLSC members under the CATR. Secondly, we explore the decision-making of CLSC by establishing decentralized and centralized models. Additionally, a comparative study of member decision-making behaviors is conducted to explore scenarios with and without the manufacturer's risk aversion. Finally, this paper introduces the incorporation of carbon trading and risk aversion cost-sharing contracts into the coordination mechanism, which supplements the pricing and coordination decision-making of CLSC under the CATR, aiming to provide scientific management guidance for the actual operations of CLSC members.

This paper is organized as follows. Section 2 presents an overview of the literature in line with the applicable work. In Section 3, we depict the problem description and fundamental assumptions. The decentralized and centralized models are formulated in section 4. The RCSC contract analysis is performed in Section 5. The numerical simulation is conducted in Section 6. Finally, we derive some managerial implications in Section 7 and end this paper with conclusions in Section 8.

## 2. Literature review

In this section, we conduct a review of studies closely aligned with our research. These studies are categorized into three main streams: WEEE management practices, remanufacturing operation decisions under the CATR, and coordination mechanisms of CLSC. To facilitate comparison and comprehension of this work, we provide a summary of pertinent literature in Table 1.

### 2.1. WEEE management practices

The rapid advancement of technological has hastened the turnover of

**Table 1**
Summary of key studies related to this paper.

| Key Related Studies | WEEE Remanufacturing | CATR | Risk Aversion | Contract strategy | Quality Heterogeneity |
|---|---|---|---|---|---|
| Liu et al. (2021) | ✓ | | | | |
| Zhang et al. (2021) | ✓ | | | | |
| Chen et al. (2020) | ✓ | ✓ | | | |
| Fang et al. (2024) | ✓ | ✓ | | | |
| Golpîra and Javanmardan (2022) | | ✓ | ✓ | | |
| Zhao et al. (2021) | | ✓ | | | Recycled Products |
| Bai et al. (2017) | | ✓ | | Revenue and promotional cost-sharing contract | |
| Xing et al. (2020) | | | ✓ | Revenue-sharing contract | |
| Zhao et al. (2022) | | | ✓ | Wholesale price and quality cost-sharing contract | Remanufactured Products |
| This study | ✓ | ✓ | ✓ | Revenue-sharing and risk joint carbon trading cost-sharing contract | Recycled Products |

electronic products, resulting in a surge of WEEE, which raises environmental concerns (Tian et al., 2022). Encompassing intricate materials, WEEE is closely associated with semiconductors, such as the core components of computers, mobile phones, and digital recorders (Tian et al., 2019), which are extensively applied across consumer electronics, communication systems, and medical instruments (Li et al., 2023b). Therefore, regardless of whether viewed from the perspective of environmental protection or economic progress, effective management of WEEE is crucial.

Countries worldwide are actively engaged in exploring effective strategies for handling WEEE. To mitigate the environmental impact of WEEE pollution and enhance resource management, researchers conducted investigations from the views of WEEE recycling systems, stakeholder participation policies, environmental impacts, and economic value (Huang et al., 2019). Compared with other EOL products, WEEE possesses unique characteristics and functions. It features a complex material structure containing environmentally hazardous elements like mercury, cadmium, and lead, alongside valuable raw materials such as copper and gold (Islam and Huda, 2018). Bressanelli et al. (2020) highlighted the substantial economic potential for WEEE recycling. Zhang et al. (2017) focused on establishing a sustainable supply chain through WEEE recycling to reduce supply risks associated with essential metals, including critical metals like indium, lithium, and cobalt. Garrido-Hidalgo et al. (2020) proposed a management framework utilizing heterogeneous IoT networks aimed at reducing costs and enhancing value in the WEEE recycling process. Meanwhile, various regulatory agencies have instituted the extended producer responsibility principle, as exemplified by the EU WEEE DIRECTIVE (Alev et al., 2020), which mandates that manufacturers participate in WEEE recycling and remanufacturing.

As an important approach for resource recovery and reuse, the CLSC is effective in establishing low-carbon production models and mitigating environmental pollution (Khazaei et al., 2017). With growing consumer preferences for low-carbon products, scholars have increasingly focused on the critical role of consumers in studying the CLSC of WEEE. Shittu et al. (2021) argued that consumer attitudes toward WEEE pose potential barriers to its reuse. They suggest that establishing high-quality reuse standards could enhance consumer confidence in WEEE remanufacturing. Qu et al. (2022) discovered that both the scale of recycling and profits of CLSC can be exuded as consumer preferences for online channels rise through establishing a dual-recycling channel decision model for WEEE. Amid rising environmental concerns, governments are increasingly implementing policies to incentivize businesses to engage in WEEE recycling and remanufacturing, drawing substantial attention from both scholars and policymakers. Wang et al. (2022) developed a four-party evolutionary game model, studying the evolving participation of consumers, collectors, and recyclers in WEEE recycling under government interventions. Liu et al. (2021) explored the effects of a deposit-refund policy and a minimal collection rate for WEEE on the operations of CLSC. Zhang et al. (2021) examined the influence of manufacturers authorizing retailers to engage in WEEE remanufacturing to investigate the optimal remanufacturing model for the CLSC under government funding policies.

However, existing research commonly assumes homogeneous quality among WEEE, overlooking the impact of recycling quality on decision-making. In WEEE management practices, quality heterogeneity affects both the quantity of WEEE and the costs of remanufacturing, which significantly influences the profits of the participants (Wang et al., 2017). Accordingly, this paper attempts to investigate the CLSC decision-making by analyzing the influence of quality heterogeneity on WEEE remanufacturing process. Furthermore, as carbon emission quotas become an essential resource in production, WEEE remanufacturing can yield substantial benefits for manufacturers. However, the implementation of CATR has rendered the decision-making environment for WEEE remanufacturing increasingly complex and dynamic, while quality heterogeneity further intensifies the challenges of operational and managerial decisions within the CLSC under CATR. Therefore, it is critically important to examine remanufacturing decisions within the CATR framework.

### *2.2. Remanufacturing decisions under cap-and-trade regulation (CATR)*

In pursuit of carbon neutrality and achieving peak carbon dioxide emissions goals, countries and enterprises are actively advocating for EOL product recycling and remanufacturing due to its low-carbon benefits (Zhu et al., 2024). With the initiation and execution of the CATR, decision-making scenarios within CLSC have become increasingly intricate and dynamic, significantly influencing the manufacturer's low-carbon operational and managerial practices (Chen et al., 2020). Factors such as fluctuating carbon trading prices, uncertainties in quota allocation, and a lack of experience collectively pose substantial challenges for manufacturers in making decisions regarding production and carbon emission reduction (Fan et al., 2023).

The introduction of carbon trading inevitably raises the cost associated with carbon emissions, thereby leading to varied decisions among members of the CLSC. To minimize the costs associated with carbon trading, many scholars have focused on carbon emission reduction strategies within CLSC from the perspectives of manufacturers. Firstly, in exploring methods for enhancing emission reduction efficiency, scholars have analyzed the factors that influence manufacturers' decisions on reducing carbon emissions. Zhao et al. (2021) proposed three production decision-making models to study the impact of uncertainties in EOL product quality and carbon emissions on the profit and costs under the CATR. Zhang et al. (2022) argued that consumers' environmental awareness and emission reduction investment costs are important factors that affect manufacturers' emission reduction initiatives. Yang et al. (2020) demonstrated that CLSC is more beneficial to carbon emission reduction by comparing other supply chains without remanufacturing. Secondly, some scholars suggest that manufacturers could outsource their emission reduction decisions or collaborate with other members. Li and Shen (2023) discovered that some manufacturers relocate a portion of new product manufacturing to unregulated regions while utilizing recycled materials for remanufacturing production in CATR regions. Xia et al. (2023) suggested that joint efforts by manufacturers and authorized remanufacturers could potentially encourage consumers to purchase remanufactured products. From the government's perspective, preferential policies such as tax, subsidies, and prioritized procurement have been introduced to offset the costs incurred by companies engaged in carbon emission reduction activities (He et al., 2023; Wu and Chiu, 2023). Li et al. (2024) devised three remanufacturing models tailored for original equipment manufacturers to account for the effects of carbon taxes and tariffs within transnational CLSC. Luo et al. (2022) found that the centralized model can achieve higher total profit than the decentralized model, while the carbon emissions of the centralized model are higher than those of the decentralized model if the carbon tax is lower. In addition, some companies are seeking to modify their original production methods by adopting emission-reducing technologies and enhancing product upgradability (Fan et al., 2023; Ma et al., 2024; Zhou et al., 2024).

However, the above-mentioned remanufacturing decisions under CATR are established based on predetermined carbon emissions per product, often neglecting the factors causing uncertainties. The uncertainty in carbon emissions caused by the heterogeneous quality of EOL products triggers unpredictability in manufacturers' carbon trading costs, adding diversity and complexity of CLSC decision-making. There is limited literature exploring the situation of quality heterogeneity, creating a theoretical gap concerning decision-making within such scenarios. Therefore, this paper integrates the CATR framework into the WEEE remanufacturing process, incorporating the impact of WEEE quality levels on carbon emissions. Additionally, given the high costs associated with carbon quota constraints, a coordination mechanism is introduced to enhance the cost-effectiveness of participants, thereby improving overall collaborative efficiency.

### 2.3. Coordination mechanisms of CLSC

Faced with challenges like information asymmetry and market fluctuations, decisions made by CLSC members frequently fail to consider the actions of other participants (Agi et al., 2021). This lack of coordination leads to issues such as double marginalization and the bullwhip effect (Zhao et al., 2022), which significantly diminish the overall performance of CLSC. In supply chain management, coordination mechanisms like information-sharing mechanisms, contract design, and strategic alliances (Fu et al., 2021; Jalali et al., 2022) help balance the interests among all parties and promote a state of harmonized operation (Kleindorfer et al., 2005).

As an essential coordination mechanism, contracts have the potential to reshape the operational framework of CLSC, drawing substantial scholars' attention (Bai et al., 2017). Yoo et al. (2015) explored and compared the impacts of the wholesale price contract, buyback contract and quantity discount contract on retail pricing and return policies. Zhang et al. (2020) designed a dual-channel revenue-sharing contract, revealing that optimal profits increase as the profit-sharing ratios rise. With the escalation of market uncertainties, participants often exhibit a propensity to avoid losses. Some scholars have endeavored to investigate the impact of risk-averse behaviors among supply chain members on decision-making processes. Addressing the uncertainty in forward supply chain demand caused by fluctuations in procuring EOL products, He (2017) constructed four contracts with different risk-sharing contracts to analyze the correlation between optimal recycling prices and remanufacturing quantities. In a CLSC with two competitive and risk-averse third-party recyclers, Xing et al. (2020) found that while a revenue-sharing contract can achieve supply chain coordination, its impact on manufacturers' low-carbon production is minimal. Zhao et al. (2022) introduced the wholesale price and quality cost-sharing contract to study the impact of participants' loss aversion on optimal CLSC decisions and utilities under remanufactured product quality control.

A vast majority of research publications on strategic decision-making studies on CLSC and the different contracts are designed to coordinate the participating supply chain members (see Table 1). However, much of this literature assumes that supply chain members are risk-neutral, overlooking the necessity for participants to consider risk factors in operational decision-making. While Xing et al. (2020) addressed risk aversion, they did not emphasis risk cost-sharing in contract design. Similarly, Zhao et al. (2022) tried to take risk aversion factors and quality heterogeneity into consideration, yet they overlooked risk cost-sharing in contract design and only evaluated the quality of remanufactured products. Owing to risk aversion behavior, manufacturers' decision-making is more prone to deviate from expectations, which puts both the quantity and revenue of remanufacturing into uncertainties. Consequently, risk factors are inevitable considerations for supply chain participants in operational decision-making. The research outcomes can render more reflective of real-world conditions by considering the behavioral preferences of these participants.

In summary, risks stemming from uncertainties due to recycling quality complicate the supply chain pricing and production decision-making process under the CATR. To foster the efficacy of CLSC operations and incentivize proactive WEEE recycling by the manufacturer, this paper proposes an RCSC in which the retailer shares not only the manufacturer's sales revenue but also carbon trading costs and losses stemming from the manufacturer's risk aversion. By considering these factors, this study aims to contribute to WEEE remanufacturing management and practice, improving our comprehension of decision-making processes within CLSC.

## 3. Model description

### 3.1. Problem description

This paper considers a CLSC composed of a manufacturer, a retailer and consumers under the CATR. Given the finite lifespan of EEE, manufacturers such as Huawei and Haier have instituted recycling systems to facilitate WEEE recycling and remanufacturing (Qu et al., 2022). Grounded in empirical evidence, this study explores the establishment of a recycling station by the manufacturer to collect WEEE with heterogeneous quality from consumers. WEEE is completely dismantled through a series of industrial processes. After undergoing procedures such as cleaning and reprocessing, the manufacturer reassembles old components and necessary new parts to produce remanufactured products that are fully equivalent to the original new products. Additionally, we consider the manufacturer simultaneously produces entirely new products composed solely of new components. Following the remanufacturing and new product manufacturing process, these products are sold to the retailer, who then makes them available to consumers. The cap carbon emissions of the manufacturer are regulated by the government under the CATR. If the carbon emissions fall below the allocated quota, the manufacturer can sell extra carbon emission quotas to obtain profit. Otherwise, the manufacturer must purchase additional carbon emission quotas through the market mechanism (Kang and Tan, 2023; Wang et al., 2018a). Heterogeneity in the collection quality of WEEE will result in uncertainty in the carbon emissions of the products' remanufacturing process, which puts the manufacturer's decision-making at risks. This paper develops two decision models to examine the decision-making processes of participants in the CLSC. In the decentralized model, affected by the CATR, the risk-averse manufacturer is in a dominant position, and the risk-neutral retailer is a follower. Based on the principle of maximizing profits, the manufacturer determines the return rate and the unit wholesale price of EEE. Then the retailer decides on the unit retail price of EEE by referencing the decisions made by the manufacturer. In the centralized model, the manufacturer and retailer cooperate and jointly decide the unit retail price of EEE and return rate of WEEE. The operating mechanism of this CLSC is shown in Fig. 1.

### 3.2. Assumptions and Notations

To better formulate the model in this paper, the following assumptions are proposed. Given the complexity of the research, some intricate conditions are simplified without altering the essence of the research.

**Assumption 1.** Through standardized production activities, remanufacturing endeavors to bring EOL parts to a state akin to new, exhibiting no compromise in functionality, performance, or quality compared to new ones (Maiti and Giri, 2015). For example, both Apple and Huawei guarantee that the remanufactured products closely resemble new ones in appearance and performance (Apple, 2018; Huawei, 2017). In this paper, we primarily focus on the impacts of WEEE recycling quality and manufacturer risk aversion on decision-making among CLSC members under the CATR. Given the complexity of the research problem, we opted to simplify some of the more intricate conditions while preserving the essence of the problem. To mitigate the influence of consumer preferences and other factors on the research results, and referencing the study conducted by Savaskan et al. (2004), we assume that there is no difference between a new product and a remanufactured product, which are sold in the same sales method and at the same price.

**Assumption 2.** There is heterogeneity in the quality of WEEE, which is represented by $q$ with a defined range of $0 < q < 1$. The costs produced per new product and per remanufactured product are expressed by $c_n$ and $c_r$, respectively. For remanufactured products, the higher the quality level of the recycled products, the lower the remanufacturing costs (Liao et al., 2020). However, the impact of quality level on remanufacturing costs weakens when high-cost components of EEE are damaged. For instance, air conditioner compressors require aluminum alloys while fan blades need plastic. In terms of the same level of recycled quality, compressors incur higher remanufacturing costs compared to fan blades. Referring to the research results of Liao et al. (2018) on the relationship between the quality of recycled products and remanufacturing costs and the formula set by Zhou et al. (2018), we assume that the unit remanufacturing cost of WEEE is a quadratic function of collection quality, i.e., $c_r = (1-q)^2 c_n$.

**Assumption 3.** Consistent with the literature (Savaskan et al., 2004), we assume that the demand functions are linear in price. The demand function can be described as $Q = \alpha - \mu p$, where $\alpha$ represents the potential market demand for equipment and $\mu$ expresses the consumer's sensitivity coefficient to the unit retail price of EEE.

**Assumption 4.** The price at which the manufacturer pays to consumers per unit of WEEE recycling is denoted as $p_r = qp_0$, where $p_0$ represents the unit maximum recycling price the manufacturer is willing to pay for consumers (Ferguson et al., 2009; Yanıkoğlu and Denizel, 2021).

**Assumption 5.** The manufacturer should invest to increase the return rate, which is defined as $\tau$. The investment cost of WEEE is expressed as $k\tau^2$, where $k$ describes the sensitivity coefficient for the investment cost of recycling WEEE (Chen et al., 2018).

**Assumption 6.** The cap carbon emissions of the manufacturer are limited by the government, which can be denoted as $E$. Governed by CATR, the manufacturer is allowed to trade emission quotas. The unit carbon emission quota trading price can be defined as $p_e$ (Chai et al., 2018; Ji et al., 2023).

**Assumption 7.** The carbon emissions produced per new product and per remanufactured product are expressed by $e_n$ and $e_r$, respectively. For remanufactured products, the higher the quality level of the recycled products, the lower the carbon emissions associated with remanufacturing (Cao et al., 2012; Zhou et al., 2018). However, the impact of quality on carbon emissions will be weakened when the high-carbon emission components of EEE are damaged. For example, when remanufacturing components with the same quality level, compressors tend to generate more carbon emissions compared to fan blades for the carbon emission coefficient of aluminum is higher than plastic. Drawing from the research results of Liao et al. (2018) on the correlations between the EOL items' quality and carbon emissions, the unit carbon emissions of remanufacturing products are a quadratic function of collection quality, i.e., $e_r = (1-q)^2 e_n$. To measure the uncertainty of carbon emissions, without loss of generality, we assume that $e_r$ follows normal distribution and satisfies: $E(e_r) = e_r$, $Var(e_r) = \sigma^2$ (Bai et al., 2020; Li et al., 2023a).

**Assumption 8.** Due to the uncertainty of carbon emissions generated during the remanufacturing, the manufacturer makes cautious decisions to mitigate losses. The coefficient of risk aversion can be described by $\eta_m$. A smaller $\eta_m$ indicates a stronger risk-taking capacity, showing that the manufacturer is less afraid of risks while making decisions (Choi et al., 2019).

**Assumption 9.** The profit function is expressed as $\pi_j^i$, where $i = D, C, SC$ represents the decentralized model, centralized model, and contract coordination decision-making model, respectively, and $j = M, R$ denotes the manufacturer and retailer, respectively.

The related parameters are shown in Table 2.

## 4. Model formulation and results analysis

### 4.1. Decentralized model

In the decentralized model, the decision-making sequence is as follows. Firstly, the manufacturer determines $\tau^D$ and $w^D$ based on the principle of maximizing profits. Secondly, the retailer decides on $p^D$ by referencing the decisions made by the manufacturer. Based on the above description and assumptions, it can be concluded that the objective profit functions of the manufacturer and retailer with the CATR are as follows.

$$\begin{aligned}\pi_M^D &= (w-c_n)Q + \tau(c_n - c_r)Q - p_r\tau Q - k\tau^2 - p_e(e_nQ + e_r\tau Q - E)\\ &= (w-c_n)(\alpha-\mu p) + \tau(\alpha-\mu p)\left[c_n - (1-q)^2 c_n\right] - p_r\tau(\alpha-\mu p) - k\tau^2\\ &\quad - p_e\left[e_n(\alpha-\mu p) + \tau e_n(\alpha-\mu p)(1-q)^2 - E\right]\end{aligned} \tag{1}$$

$$\pi_R^D = (p-w)Q = (p-w)(\alpha-\mu p) \tag{2}$$

For the manufacturer, the profit function includes three parts. The first part is the profit from selling products. The second part is the cost of

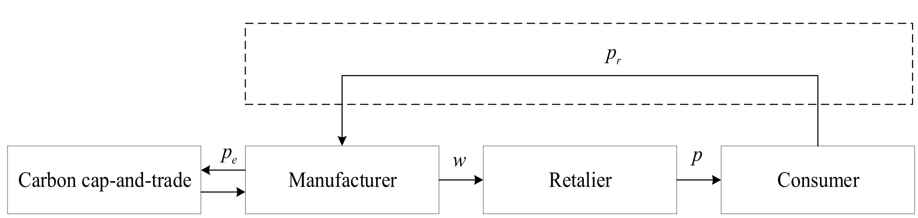


**Fig. 1.** Framework of the model.

**Table 2**
Definition of parameters.

| Variables/Parameters | Definition |
|---|---|
| Decision variables | |
| $w^i$ | Unit wholesale price of EEE, $i = D, C, SC$ |
| $p^i$ | Unit retail price of EEE, $i = D, C, SC$ |
| $\tau^i$ | Return rate of WEEE, $i = D, C, SC$ |
| Parameters | |
| $c_n$ | Unit manufacturing cost of new product |
| $c_r$ | Unit remanufacturing cost of WEEE |
| $\alpha$ | Potential market size, $\alpha > 0$ |
| $Q$ | Demand function of the manufacturer. |
| $\mu$ | Price sensitivity coefficient, $\mu > 0$ |
| $k$ | Sensitivity coefficient for the investment cost of WEEE recycling |
| $e_n$ | Unit carbon emissions of new product |
| $e_r$ | Unit carbon emissions of remanufactured product |
| $p_0$ | Unit maximum recycling price of WEEE |
| $q$ | Collection quality of WEEE, $q \in (0, 1)$ |
| $p_r$ | Unit recycling price of WEEE |
| $E$ | Carbon emissions cap allocated to the manufacturer |
| $p_e$ | Unit carbon emission quota trading price |
| $\eta_M$ | Coefficient of risk aversion |
| $\pi_j^i$ | Profit function, $i = D, C, SC, j = M, R$ |

WEEE recycling. The third part $p_e(e_nQ + e_r\tau Q - E)$ is the trading cost/revenue under the CATR. If $p_e(e_nQ + e_r\tau Q - E) > 0$, i.e., if the actual carbon emissions exceed the cap quotas, then the manufacturer should pay for the excess carbon emission. Conversely, if $p_e(e_nQ + e_r\tau Q - E) < 0$, the manufacturer can sell the surplus carbon quota in the carbon trading market to gain additional revenue. For the retailer, the profit function includes only the profit from selling products.

Facing the uncertainties surrounding carbon emissions during the remanufacturing process caused by the heterogeneity quality of WEEE, the manufacturer exhibits a risk-averse attitude in the decision-making process. According to the mean-variance theory, the manufacturer's and retailer's expected utility are rewritten as follows.

$$\begin{aligned} U(\pi_M^D) &= E(\pi_M^D) - \eta_M\sqrt{VarE(\pi_M^D)} \\ &= (w - c_n)(\alpha - \mu p) - qp_0\tau(\alpha - \mu p) + \tau(\alpha - \mu p)\left[c_n - (1-q)^2 c_n\right] \\ &\quad - p_e\left[e_n(\alpha - \mu p) + \tau e_n(\alpha - \mu p)(1-q)^2 - E\right] - k\tau^2 - \eta_M p_e \tau(\alpha - \mu p)\sigma \end{aligned} \tag{3}$$

$$U(\pi_R^D) = E(\pi_R^D) = (p - w)(\alpha - \mu p) \tag{4}$$

Following the principle of reverse reasoning, assuming that the return rate of WEEE and the unit wholesale price of EEE are determined, we can get the optimal unit retail price of EEE $p^{D^*}$. Then the manufacturer's optimal return rate of WEEE $\tau^{D^*}$ and unit wholesale price of EEE $w^{D^*}$ can be obtained by substituting it into (3). The optimal solutions of the decision variables are derived as follows.

$$w^{D^*} = \frac{\mu\left\{4k(c_n + p_e e_n) - \alpha[(c_n + p_e e_n)q^2 + q(p_0 - 2c_n - 2p_e c_n) + p_e(e_n + \eta_M\sigma)]^2\right\} + 4\alpha k}{\mu\left\{8k - \mu[(c_n + p_e e_n)q^2 + q(p_0 - 2c_n - 2p_e c_n) + p_e(e_n + \eta_M\sigma)]^2\right\}} \tag{5}$$

$$p^{D^*} = \frac{\mu\left\{2k(c_n + p_e e_n) - \alpha[(c_n + p_e e_n)q^2 + q(p_0 - 2c_n - 2p_e c_n) + p_e(e_n + \eta_M\sigma)]^2\right\} + 6\alpha k}{\mu\left\{8k - \mu[(c_n + p_e e_n)q^2 + q(p_0 - 2c_n - 2p_e c_n) + p_e(e_n + \eta_M\sigma)]^2\right\}} \tag{6}$$

$$\tau^{D^*} = \frac{[\mu(c_n + p_e e_n) - \alpha][(c_n + p_e e_n)q^2 + q(p_0 - 2c_n - 2p_e c_n) + p_e(e_n + \eta_M\sigma)]}{8k - \mu[(c_n + p_e e_n)q^2 + q(p_0 - 2c_n - 2p_e c_n) + p_e(e_n + \eta_M\sigma)]^2} \tag{7}$$

Substituting Eqs. (5)–(7) into Eqs. (3) and (4), the profits of the manufacturer and retailer can be obtained as follows.

$$U(\pi_M^{D^*}) = \frac{\begin{array}{c} 2\mu^2 p_e^2\left[qE(p_0 + qc_n - 2c_n)\left(e_n + e_n q^2 + \sigma\eta_M - 2qe_n\right) - \frac{1}{2}ke_n^2\right] \\ + p_e\left\{\left[Eq^2(p_0 + qc_n - 2c_n)^2 - 2kc_n e_n\right] - k(8E - 2\alpha e_n)\right\} \\ + E\mu^2 p_e^3\left(e_n + e_n q^2 + \sigma\eta_M - 2qe_n\right)^2 - kc_n 2\left(\mu^2 c_n - 2\alpha\right) \end{array}}{\mu\left\{8k - \mu[(c_n + p_e e_n)q^2 + q(p_0 - 2c_n - 2p_e c_n) + p_e(e_n + \eta_M\sigma)]^2\right\}} \tag{8}$$

$$U(\pi_R^{D^*}) = = \frac{4k^2[(c_n + p_e e_n)\mu - \alpha]^2}{\mu\left\{8k - \mu[(c_n + p_e e_n)q^2 + q(p_0 - 2c_n - 2p_e c_n) + p_e(e_n + \eta_M\sigma)]^2\right\}^2} \tag{9}$$

**Proposition 1**. The return rate of WEEE will increase, and both the unit wholesale and retail prices of EEE will decrease with the improvement in the collection quality of WEEE if $0 < q < \frac{2(c_n + p_e e_n) - p_0}{2(c_n + p_e e_n)}$. If $\frac{2(c_n + p_e e_n) - p_0}{2(c_n + p_e e_n)} < q < 1$, the situation will be the opposite with the collection quality of WEEE improving.

**Proof.** The first derivative concerning q is taken for the equilibrium solutions in the decentralized model.

$$\frac{\partial w^{D^*}}{\partial q}=\frac{k[(c_n+p_ee_n)\mu-\alpha]\left[\frac{1}{2}p_0+q(c_n+p_ee_n)-p_ee_n-c_n\right]\left[(c_n+p_ee_n)q^2+(p_0-2c_n-2p_ec_n)q+p_e(e_n+\eta_M\sigma)\right]}{\left\{k-\frac{1}{8}\mu[(c_n+p_ee_n)q^2+q(p_0-2c_n-2p_ec_n)+p_e(e_n+\eta_M\sigma)]^2\right\}^2}$$

$$\frac{\partial p^{D^*}}{\partial q}=\frac{k[(c_n+p_ee_n)\mu-\alpha]\left[\frac{1}{2}p_0+q(c_n+p_ee_n)-p_ee_n-c_n\right]\left[(c_n+p_ee_n)q^2+(p_0-2c_n-2p_ec_n)q+p_e(e_n+\eta_M\sigma)\right]}{\left\{k-\frac{1}{8}\mu[(c_n+p_ee_n)q^2+q(p_0-2c_n-2p_ec_n)+p_ee_n]^2\right\}^2}$$

$$\frac{\partial \tau^{D^*}}{\partial q}=\frac{[\mu(c_n+p_ee_n)-\alpha]\left[\frac{1}{2}p_0+q(c_n+p_ee_n)-p_ee_n-c_n\right]\left[k+\mu\left[(c_n+p_ee_n)q^2+(p_0-2c_n-2p_ec_n)q+p_ee_n(e_n+\eta_M\sigma)\right]^2\right]}{4[(c_n+p_ee_n)q^2+(p_0-2c_n-2p_ec_n)q+p_ee_n]\left[(c_n+p_ee_n)q^2+(p_0-2c_n-2p_ec_n)q+p_ee_n\right]\left[(c_n+p_ee_n)q^2+(p_0-2c_n-2p_ec_n)q+p_ee_n\right]^2\right]^2}$$

Therefore, if $0<q<\frac{2(c_n+p_ee_n)-p_0}{2(c_n+p_ee_n)}$, $\frac{\partial\tau^{D^*}}{\partial q}>0$, $\frac{\partial p^{D^*}}{\partial q}<0$, and $\frac{\partial w^{D^*}}{\partial q}<0$. And if $\frac{2(c_n+p_ee_n)-p_0}{2(c_n+p_ee_n)}<q<1$, we can obtain that $\frac{\partial\tau^{D^*}}{\partial q}<0$, $\frac{\partial p^{D^*}}{\partial q}>0$, and $\frac{\partial w^{D^*}}{\partial q}>0$.

Proposition 1 shows that the decision-making of supply chain members is affected by the quality level of WEEE. If $0<q<\frac{2(c_n+p_ee_n)-p_0}{2(c_n+p_ee_n)}$, consumers will actively participate in recycling high-quality WEEE due to the unit recycling price increases with the increase in collection quality. At this time, the return rate of WEEE will also increase accordingly. In the process of WEEE remanufacturing, the collection quality has a negative influence on the remanufacturing cost, namely, the higher collection quality of WEEE will lead to the lower remanufacturing cost. In other words, the manufacturer needs to spend more effort and money on remanufacturing when collection quality is lower, which will lead to a higher wholesale price purchased by the retailer from the manufacturer and an increasing the unit retail price of EEE for the consumer.

If $\frac{2(c_n+p_ee_n)-p_0}{2(c_n+p_ee_n)}<q<1$, the wholesale price and retail price per unit of EEE will increase as the collection quality improves, and the return rate decreases. The reason for this is that the cost savings from remanufacturing are less than the cost of recycling, causing the manufacturer to reduce the WEEE return rate. At the same time, the manufacturer and retailer will raise prices to reduce losses.

### 4.2. Centralized model

In the centralized model, the manufacturer and retailer cooperate and jointly decide the unit retail price of EEE and return rate of WEEE to maximize the total profit of the supply chain. The total expected profit function of the CLSC considering the manufacturer's risk aversion and the WEEE collection quality is illustrated in Eq. (10).

$$\begin{aligned}U(\pi^C)=&(w-c_n)(\alpha-\mu p)-qp_0\tau(\alpha-\mu p)+\tau(\alpha-\mu p)\left[c_n-(1-q)^2c_n\right]-p_e[e_n(\alpha-\mu p)\\&+\tau e_n(\alpha-\mu p)(1-q)^2-E\big]-k\tau^2-\eta_Mp_e\tau(\alpha-\mu p)\sigma+(p-w)(\alpha-\mu p)\end{aligned}\tag{10}$$

The first derivatives of Eq. (10) concerning the variables $p$ and $\tau$ are calculated. Additionally, we set $\frac{\partial\pi^C}{\partial p}$ and $\frac{\partial\pi^C}{\partial\tau}$ to zero, leading to the following expressions.

$$p^{C^*}=\frac{\mu\left\{2k(c_n+p_ee_n)-\alpha[(c_n+p_ee_n)q^2+q(p_0-2c_n-2p_ec_n)+p_e(e_n+\eta_M\sigma)]^2\right\}+2\alpha k}{\mu\left\{4k-\mu[(c_n+p_ee_n)q^2+q(p_0-2c_n-2p_ec_n)+p_e(e_n+\eta_M\sigma)]^2\right\}}\tag{11}$$

$$\tau^{C^*}=\frac{[(c_n+p_ee_n)\mu-\alpha][(c_n+p_ee_n)q^2+q(p_0-2c_n-2p_ec_n)+p_e(e_n+\eta_M\sigma)]}{4k-\mu[(c_n+p_ee_n)q^2+q(p_0-2c_n-2p_ec_n)+p_e(e_n+\eta_M\sigma)]^2}\tag{12}$$

Hence, the total profit of the supply chain can be expressed as follows.

$$U(\pi^{C^*})==\frac{\begin{aligned}&2\mu^2p_e^2\left[qE(p_0+qc_n-2c_n)\left(e_n+e_nq^2+\sigma\eta_M-2qe_n\right)-\frac{1}{2}ke_n^2\right]\\&+p_e\left[Eq^2(p_0+qc_n-2c_n)^2-2kc_ne_n\right]-k\mu[(4E-2\alpha e_n)-2\alpha c_n]\\&+E\mu^2p_e^3\left(e_n+e_nq^2+\sigma\eta_M-2qe_n\right)^2-k\alpha^2\end{aligned}}{\mu\{8k-\mu[(c_n+p_ee_n)q^2+q(p_0-2c_n-2p_ec_n)+p_e(e_n+\eta_M\sigma)]\}}\tag{13}$$

**Proposition 2**. Compared with the decentralized model, the centralized model exhibits a higher optimal return rate and demand, along with a lower retail price per unit of EEE, i.e., $\tau^{D^*} < \tau^{C^*}$, $p^{D^*} > p^{C^*}$, $Q^{D^*} < Q^{C^*}$.

**Proof.** It is easy to see that,

$$\tau^{D^*} - \tau^{C^*} = \frac{-[(c_n + p_e e_n)\mu - \alpha]k^2}{4\mu\left\{k - \frac{1}{4}\mu\left[(c_n + p_e e_n)q^2 + q(p_0 - 2c_n - 2p_e c_n) + p_e e_n\right]^2\right\}} < 0 \quad p^{D^*} - p^{C^*} = \frac{[(c_n + p_e e_n)\mu - \alpha][(c_n + p_e e_n)q^2 + q(p_0 - 2c_n - 2p_e c_n) + p_e e_n]k^2}{4\mu\left\{k - \frac{1}{4}\mu\left[(c_n + p_e e_n)q^2 + q(p_0 - 2c_n - 2p_e c_n) + p_e e_n\right]^2\right\}} > 0 \quad Q^{D^*} - Q^{C^*} = \frac{-[\alpha - (c_n + p_e e_n)\mu]k^2}{4\mu\left\{k - \frac{1}{4}\mu\left[(c_n + p_e e_n)q^2 + q(p_0 - 2c_n - 2p_e c_n) + p_e e_n\right]^2\right\}} < 0$$

$$\left\{k - \frac{1}{4}\mu\left[(c_n + p_e e_n)q^2 + q(p_0 - 2c_n - 2p_e c_n) + p_e e_n\right]^2\right\}$$

$$\left\{k - \frac{1}{4}\mu\left[(c_n + p_e e_n)q^2 + q(p_0 - 2c_n - 2p_e c_n) + p_e e_n\right]^2\right\}$$

$$\left\{k - \frac{1}{4}\mu\left[(c_n + p_e e_n)q^2 + q(p_0 - 2c_n - 2p_e c_n) + p_e e_n\right]^2\right\}$$

Hence, we can obtain that $\tau^{D^*} < \tau^{C^*}$, $p^{D^*} > p^{C^*}$, $Q^{D^*} < Q^{C^*}$.

The findings indicate that the retailer will raise the unit retail price of EEE to boost profits under the decentralized model. In the decentralized model, the unit retail price of EEE is higher than in the centralized model, with market demand inversely proportional to retail prices. As market demand inversely correlates with retail price, elevated retail prices for EEE diminish consumer purchasing interest, resulting in decreased demand under the decentralized model. This leads to a slower circulation of products in the market, where consumers may prefer repair over participation in recycling activities, ultimately leading to a decline in WEEE return rates. Therefore, there is still a potential for enhancement in the WEEE return rate under the decentralized model.

### 4.3. Extension and comparison

To explore a deeper understanding of the impact of risk aversion on supply chain decision-making, we conduct a study of member decision-making behavior in the decentralized model without accounting for the manufacturer's risk aversion factor. The results are compared with those in Section 4.1 where the manufacturer's risk aversion is considered.

The profits of the manufacturer and retailer are rewritten as follows.

$$\begin{aligned}\pi_M^D &= (w - c_n)Q - p_r\tau Q + \tau Q(c_n - c_r) - p_e(e_n Q + e_r\tau Q - E) - k\tau^2 \\ &= (w - c_n)(\alpha - \mu p) - qp_0\tau(\alpha - \mu p) + \tau(\alpha - \mu p)\left[c_n - (1 - q)^2 c_n\right] \\ &\quad - p_e\left[e_n(\alpha - \mu p) + e_n\tau(\alpha - \mu p)(1 - q)^2 - E\right] - k\tau^2\end{aligned} \tag{14}$$

$$\pi_R^D = (p - w)Q = (p - w)(\alpha - \mu p) \tag{15}$$

The optimal decisions of the manufacturer and retailer are as follows.

$$w^{D^{**}} = \frac{\mu\left\{4k(c_n + p_e e_n) - \alpha[(c_n + p_e e_n)q^2 + q(p_0 - 2c_n - 2p_e e_n) + p_e e_n]^2\right\} + 4\alpha k}{\mu\left\{8k - \mu[(c_n + p_e e_n)q^2 + q(p_0 - 2c_n - 2p_e e_n) + p_e e_n]^2\right\}} \tag{16}$$

$$p^{D^{**}} = \frac{\mu\left\{2k(c_n + p_e e_n) - \alpha[(c_n + p_e e_n)q^2 + q(p_0 - 2c_n - 2p_e e_n) + p_e e_n]^2\right\} + 6\alpha k}{\mu\left\{8k - \mu[(c_n + p_e e_n)q^2 + q(p_0 - 2c_n - 2p_e e_n) + p_e e_n]^2\right\}} \tag{17}$$

$$\tau^{D^{**}} = \frac{[(c_n + p_e e_n)\mu - \alpha][(c_n + p_e e_n)q^2 + (p_0 - 2c_n - 2p_e e_n)q + p_e e_n]}{8k - \mu[(c_n + p_e e_n)q^2 + (p_0 - 2c_n - 2p_e e_n)q + p_e e_n]^2} \tag{18}$$

The profits of the manufacturer and retailer can be expressed as follows.

$$\pi_M^{D^{**}} = \frac{\mu^2\left\{p_e\left[2kc_n e_n - Eq^2(p_0 + qc_n - 2c_n)^2\right] - 2e_n p_e^2\left[qE(1 - q)^2(p_0 + qc_n - 2c_n) - Ee_n^2 p_e^3(1 - q)^4 - \frac{1}{2}ke_n\right]\right\} + 8k\left[p_e\left(E - \frac{1}{4}\alpha e_n\right) - \frac{1}{4}\alpha c_n\right] + k\alpha^2 + k\mu^2 c_n^2}{\mu\left\{8k - \mu[(c_n + p_e e_n)q^2 + (p_0 - 2c_n - 2p_e e_n)q + p_e e_n]^2\right\}} \tag{19}$$

$$\pi_R^{D**} = \frac{4k^2[(c_n + p_e e_n)\mu - \alpha]^2}{\mu\{8k - \mu[(c_n + p_e e_n)q^2 + (p_0 - 2c_n - 2p_e e_n)q + p_e e_n]^2\}^2} \tag{20}$$

**Proposition 3**. *If $0 < q < \frac{2(c_n+p_e e_n)-p_0}{2(c_n+p_e e_n)}$, both the wholesale and retail prices per unit of EEE are monotonically decreasing functions of collection quality, while the return rate is a monotonically increasing function of collection quality. However, if $\frac{2(c_n+p_e e_n)-p_0}{2(c_n+p_e e_n)} < q < 1$, the result is just the opposite.*

***Pro*****of**. It is easy to get that,

$$\frac{\partial w^{D**}}{\partial q} = \frac{k[(c_n + p_e e_n)\mu - \alpha]\left[\frac{1}{2}p_0 + q(c_n + p_e e_n) - p_e e_n - c_n\right][(c_n + p_e e_n)q^2 + (p_0 - 2c_n - 2p_e c_n)q + p_e e_n]}{\left\{k - \frac{1}{8}\mu[(c_n + p_e e_n)q^2 + q(p_0 - 2c_n - 2p_e c_n) + p_e e_n]^2\right\}^2}$$

$$\frac{\partial p^{D**}}{\partial q} = \frac{k[(c_n + p_e e_n)\mu - \alpha]\left[\frac{1}{2}p_0 + q(c_n + p_e e_n) - p_e e_n - c_n\right][(c_n + p_e e_n)q^2 + (p_0 - 2c_n - 2p_e c_n)q + p_e e_n]}{\left\{k - \frac{1}{8}\mu[(c_n + p_e e_n)q^2 + q(p_0 - 2c_n - 2p_e c_n) + p_e e_n]^2\right\}^2}$$

$$\frac{\partial \tau^{D**}}{\partial q} = \frac{[\mu(c_n + p_e e_n) - \alpha]\left[\frac{1}{2}p_0 + q(c_n + p_e e_n) - p_e e_n - c_n\right]\left[k + \mu[(c_n + p_e e_n)q^2 + (p_0 - 2c_n - 2p_e c_n)q + p_e e_n]^2\right]}{4[(c_n + p_e e_n)q^2 + (p_0 - 2c_n - 2p_e c_n)q + p_e e_n][(c_n + p_e e_n)q^2 + (p_0 - 2c_n - 2p_e c_n)q + p_e e_n][(c_n + p_e e_n)q^2 + (p_0 - 2c_n - 2p_e c_n)q + p_e e_n]^2]^2}$$

Therefore, if $0 < q < \frac{2(c_n+p_e e_n)-p_0}{2(c_n+p_e e_n)}, \frac{\partial p^{D**}}{\partial q} < 0$, and $\frac{\partial w^{D**}}{\partial q} < 0, \frac{\partial \tau^{D**}}{\partial q} > 0$, while $\frac{2(c_n+p_e e_n)-p_0}{2(c_n+p_e e_n)} < q < 1, \frac{\partial p^{D*}}{\partial q} > 0, \frac{\partial w^{D**}}{\partial q} > 0$, and $\frac{\partial \tau^{D**}}{\partial q} < 0$.

Proposition 3 states that if $0 < q < \frac{2(c_n+p_e e_n)-p_0}{2(c_n+p_e e_n)}$, remanufacturing costs decrease as the collection quality level increases, consequently reducing the unit wholesale price of EEE. In response, the retailer lowers the unit retail price of EEE to stimulate demand, ultimately leading to an increase in market demand. This increase in demand results in an uptick in carbon emissions, as both new equipment production and the remanufacturing of WEEE generate carbon emissions under CATR. As carbon emissions rise, the manufacturer must pay higher prices for carbon emission quotas. Therefore, if the collection quality is high, the manufacturer can reduce the return rate of WEEE to mitigate the cost of carbon trading.

**Proposition 4**. When the manufacturer's risk aversion is considered, the manufacturer tends to raise the unit wholesale price of EEE and decrease the return rate of WEEE, while the retailer opts to increase the unit retail price of EEE.

**Proof.** It is easy to see that,

$$p^{D*} - p^{D**} =$$

$$\frac{1}{32}\frac{kp_e\eta_M[\mu(c_n + p_e e_n) - \alpha][(2c_n + 2p_e e_n)q^2 + q(2p_0 - 4c_n - 4p_e c_n) + p_e(2e_n + \eta_M\sigma)]\sigma^2}{\left\{k - \frac{1}{8}\mu[(c_n + p_e e_n)q^2 + q(p_0 - 2c_n - 2p_e e_n) + p_e e_n]^2\right\}\left\{k - \frac{1}{8}\mu[(c_n + p_e e_n)q^2 + q(p_0 - 2c_n - 2p_e c_n) + p_e(e_n + \eta_M\sigma)]^2\right\}} > 0$$

$$w^{D*} - w^{D**} =$$

$$\frac{1}{16}\frac{kp_e\eta_M[\mu(c_n + p_e e_n) - \alpha][(2c_n + 2p_e e_n)q^2 + q(2p_0 - 4c_n - 4p_e c_n) + p_e(2e_n + \eta_M\sigma)]\sigma^2}{\left\{k - \frac{1}{8}\mu[(c_n + p_e e_n)q^2 + q(p_0 - 2c_n - 2p_e e_n) + p_e e_n]^2\right\}\left\{k - \frac{1}{8}\mu[(c_n + p_e e_n)q^2 + q(p_0 - 2c_n - 2p_e c_n) + p_e(e_n + \eta_M\sigma)]^2\right\}} > 0$$

$$\tau^{D*} - \tau^{D**} =$$

$$\frac{1}{8}\frac{p_e\eta_M[\mu(c_n + p_e e_n) - \alpha]\{k + \frac{1}{8}\mu[(c_n + p_e e_n)q^2 + q(p_0 - 2c_n - 2p_e e_n) + p_e e_n] \times [(c_n + p_e e_n)q^2 + q(p_0 - 2c_n - 2p_e c_n) + p_e(e_n + \eta_M\sigma)]\}\sigma^2}{\left\{k - \frac{1}{8}\mu[(c_n + p_e e_n)q^2 + q(p_0 - 2c_n - 2p_e e_n) + p_e e_n]^2\right\}\left\{k - \frac{1}{8}\mu[(c_n + p_e e_n)q^2 + q(p_0 - 2c_n - 2p_e c_n) + p_e(e_n + \eta_M\sigma)]^2\right\}} < 0$$

Hence, we can obtain that $p^{D**} > p^{D*}, w^{D**} > w^{D*}, \tau^{D**} < \tau^{D*}$.

We can derive from Proposition 4 that the degree of risk aversion will increase the wholesale and retail prices per unit of EEE while reducing the return rate. On the one hand, the manufacturer raises the unit wholesale price of EEE to boost profits and mitigate potential losses, while the retailer similarly increases the unit retail price of EEE. On the other hand, the manufacturer will reduce the WEEE return rate to avoid the risk of carbon emissions uncertainty caused by the heterogeneity quality of WEEE.

**Proposition 5**. . The manufacturer's risk aversion can reduce the impact of collection quality on the optimal decision.

Proof. Comparing Proposition 3 with Proposition 1, it follows that $\frac{\partial p^{D^*}}{\partial q} - \frac{\partial p^{D^{**}}}{\partial q} < 0$, $\frac{\partial w^{D^*}}{\partial q} - \frac{\partial w^{D^{**}}}{\partial q} < 0$, $\frac{\partial \tau^{D^*}}{\partial q} - \frac{\partial \tau^{D^{**}}}{\partial q} < 0$.

Proposition 5 states that when the manufacturer's risk aversion is considered, the impact of collection quality on supply chain decisions decreases. This is mainly due to the collection quality affects carbon emissions, while the risk aversion characteristic is to reduce the losses caused by carbon emissions, thereby risk aversion can reduce the impact of the collection quality. This further underscores the importance of considering the manufacturer's risk aversion in decision-making, as it aligns more closely with the actual decision-making environment, thereby facilitating more effective decision-making among supply chain members.

## 5. Contract analysis

### 5.1. Contract Formats discussion

The production of new products and the WEEE remanufacturing generate carbon emissions. The manufacturer engages in buying and selling carbon emission quotas to maintain normal operations under the CATR. Aiming at reducing carbon emissions, the manufacturer tends to invest a lot of money to increase the return rate of WEEE. However, if the manufacturer has to bear the costs of both recycling and carbon trading, the wholesale and retail prices of products will inevitably increase, resulting in lower demand for EEE.

Based on the optimal decision, it can be seen that the retail price is directly proportional to the unit carbon emission quota trading price, and the WEEE return rate is inversely proportional to it. The uncertainty of carbon emissions generated during the remanufacturing process puts the manufacturer's decision-making at risk. To achieve CLSC coordination and incentivize proactive WEEE recycling by the manufacturer, we propose a sharing contract as being a combination of the RCSC in which the retailer shares the manufacturer's carbon trading costs and losses resulting from the manufacturer's risk aversion in proportion $\xi$, alongside a proportion $1-\varphi$ of sales revenue. The profit functions of the manufacturer and retailer are illustrated in Eq. (22) and Eq. (23) respectively.

$$\begin{aligned}\pi_M^{SC} &= \varphi(w+p)(\alpha-\mu p) - c_n(\alpha-\mu p) + \tau(\alpha-\mu p)\left[c_n-(1-q)^2c_n\right] \\ &-k\tau^2-(1-\xi)\left\{p_e\left[e_n(\alpha-\mu p)+e_n\tau(\alpha-\mu p)(1-q)^2-E\right]+\eta_M p_e\tau(\alpha-\mu p)\sigma^2\right\}\end{aligned} \tag{21}$$

$$\begin{aligned}\pi_R^{SC} &= (1-\varphi)(p+w)(\alpha-\mu p) - w(\alpha-\mu p) \\ &-\xi\left\{p_e\left[e_n(\alpha-\mu p)+e_n\tau(\alpha-\mu p)(1-q)^2-E\right]+\eta_M p_e\tau(\alpha-\mu p)\sigma^2\right\}\end{aligned} \tag{22}$$

### 5.2. Supply chain coordination

In the RCSC, the decision sequence follows the same order as the decentralized model. The dominating manufacturer first determines the return rate of WEEE $\tau^{SC}$ and the unit wholesale price of EEE $w^{SC}$, and then the retailer sets the unit retail price of EEE $p^{SC}$. We derive the optimal retail price per unit EEE of the retailer as follows.

$$p^{SC^*} = \frac{\alpha(\varphi-1)-\mu\left\{\xi p_e\left\{\eta_M\tau\sigma+e_n\left[1+\tau(1-q)^2\right]\right\}-w\varphi\right\}}{2\mu(\varphi-1)} \tag{23}$$

To enhance the operational efficiency of the supply chain and the profits of the members, setting $p^{SC^*}=p^{C^*}, \tau^{SC^*}=\tau^{C^*}$, the unit wholesale price of EEE under the contract is found in Eq. (25).

$$w^{SC^*} = \frac{-M_1\left[\sigma\eta_M(1-q)^2e_n\right]p_e^2+(M_2e_nq^3+M_3q^2+M_4)p_e-M_5}{\varphi\left\{4k-\mu[(c_n+p_ee_n)q^2+q(p_0-2c_n-2p_ec_n)+p_e(e_n+\sigma\eta_M]^2\right\}} \tag{24}$$

Where,

$$M_1 = \alpha(\xi+\varphi-1)\left[e_n\left(q^2+2q-1\right)-\sigma\eta_M\right]-\xi\mu\left[e_n(p_0q-c_n)-c_n\sigma\eta_M\right]$$

$$M_2 = \mu\xi c_np_0+\alpha(\xi+2\varphi-2)\left[p_0+c_n\left(q^4e_n-4\right)\right]$$

$$\begin{aligned}M_3 &= e_n\left[(\xi+2\varphi-2)(5c_n-2p_0)-\mu\xi\left(2p_0c_n+c_n^2-p_0^2\right)\right]-\sigma c_n\eta_M[\mu\xi c_n \\ &-\alpha(\xi+2\varphi-2)]\end{aligned}$$

$$M_4 = (p_0-2c_n)(\sigma\eta_M+e_n)[\alpha(\xi+2\varphi-2)-\mu\xi c_n]-4kc_n(\xi+\varphi-1)$$

$$M_5 = (\varphi-1)\left\{\left[4k-2\alpha p_0(q-2)q^2-\alpha q^2\left[p_0^2+(q-2)^2c_n^2\right]\right\}\right.$$

If the profits of the manufacturer and retailer are to increase, there is a high likelihood that they will accept the contract, i.e., $\pi_M^{SC^*} > \pi_M^{D^*}$ and $\pi_R^{SC^*} > \pi_R^{D^*}$. At this point, the range of values for $\varphi$ and $\xi$ can be determined.

$$\frac{16k^2+\xi\mu^2q^4(p_0+qc_n-2c_n)^4-8k\xi\mu q^2(p_0+qc_n-2c_n)^2}{32\mu\left[-\frac{1}{8}q^2(qc_n+p_0-2c_n)^2\mu+k\right]} < \varphi < \frac{192k^3+16k\xi\mu^2q^4(p_0+qc_n-2c_n)^4-\xi\mu^3q^6(p_0+qc_n-2c_n)^6-\mu(64\xi+32)q^2k^2(p_0+qc_n-2c_n)^2}{256\mu\left[-\frac{1}{8}q^2(qc_n+p_0-2c_n)^2\mu+k\right]^2}$$

The detailed analysis of RCSC is presented in Section 6.

## 6. Numerical study

From the model's description, it becomes evident that the heterogeneity in the collection quality of WEEE contributes to uncertainties in carbon emissions and remanufacturing costs, consequently leading to risk aversion of the manufacturer. When carbon emissions surpass governmental limits, the manufacturer is obligated to purchase carbon emission quotas under the CATR. Consequently, the unit carbon emission quota trading price indirectly influences the manufacturer's risk aversion, as the price impacts the transaction cost of carbon emission. To explore the detailed effects of crucial parameters on optimal decisions, the numerical experiments are studied in this section.

Recently, several home appliance manufacturers have taken proactive steps in WEEE processing. Third-party collection platforms like Huishoubao and Aihuishou also engage in gathering EOL mobile phones, computers, and various digital devices (Yang et al., 2020). During the recycling process, there is a certain discount on product prices. The recycling prices, which depreciate due to varying levels of wear and tear, are typically defined based on the quality of the product. Depending on the product's value, the maximum recycling price ranges from 50% to 80% of the original product price. For instance, the original price of the Huawei Mate40 Pro is 6599 yuan, with a maximum unit recycling price of up to 4700 yuan, which is 71% of the original price. In this paper, to simplify the simulation process, we set the unit manufacturer's maximum WEEE recycling price $p_0 = 3$, and the manufacturing cost per unit of new product $c_n = 4$. Depending on the collection quality of WEEE, the unit recycling price will generate corresponding discounts. Based on the emission data investigation for the Huawei Mate40 Pro, the upstream emissions per phone are 81.09 kgCO2-eq, with 72.91 for raw material and component manufacturing, 6.06 for product transportation and retail, and 2.12 for product assembly, where raw material and component manufacturing account for 44.96% of the total emissions. However, Huawei's carbon emission calculation for smartphones only includes upstream emission data, and it is difficult to obtain full lifecycle data. To make the data in this paper more realistic, we set the unit carbon emissions of the new product to 4 and the carbon emissions cap allocated to the manufacturer to 10, i.e. $e_n = 4, E = 10$. Referring to relevant literature and making adjustments based on the specific context (Giri et al., 2017; Guo et al., 2023), the parameter values involved in this chapter are as follows: $\alpha = 3, \mu = 0.1, c_n = 4, k = 1, p_0 = 3, e_n = 4, E = 10, \sigma = 1$.

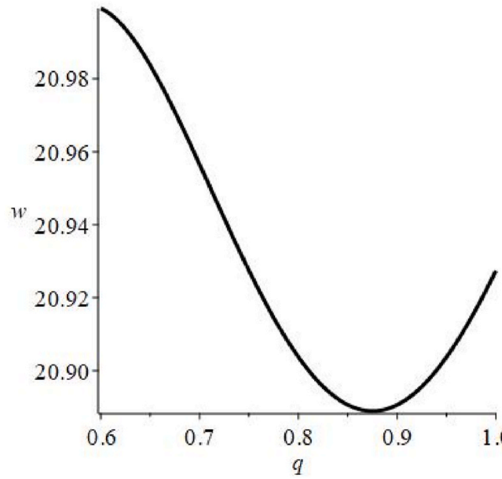


**Fig. 2.** The effect of collection quality on the unit wholesale price of EEE.

### 6.1. Analysis of single factors' impacts on pricing and profits

In this section, numerical simulation is conducted to illustrate the detailed influence of crucial parameters on optimal decisions including quality heterogeneity, unit carbon emission quota trading price, and manufacturer's risk aversion.

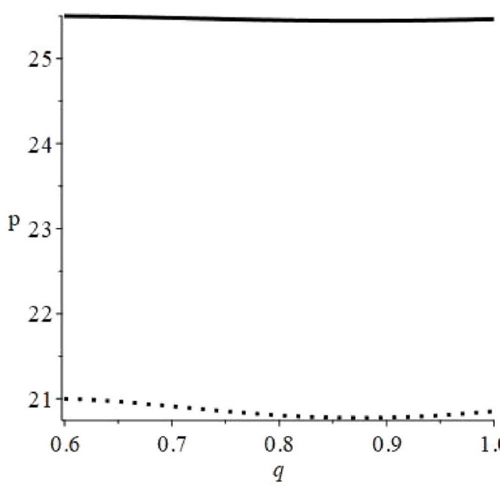


**Fig. 3.** The effect of collection quality on the unit retail price of EEE.

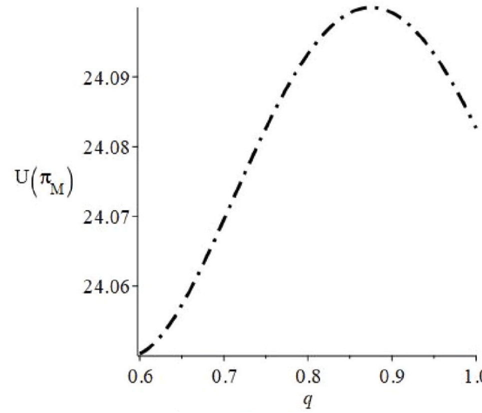


**Fig. 5.** The effect of collection quality on the manufacturer's profit.

#### 6.1.1. The impact of quality heterogeneity on pricing and profits

Figs. 2–7 depict the impact of collection quality on pricing decisions, member profits, return rate, and profit of the CLSC, assuming $p_e = 6$ at this time.

As shown in Figs. 2 and 3, within a certain range of collection quality, the unit wholesale price and retail price of EEE decrease as the collection quality increases. Within this range, as the collection quality level rises, remanufacturing costs decrease along with carbon emissions. The manufacturer is more inclined to collect high-quality WEEE for remanufacturing rather than engaging in the manufacturing of new products,

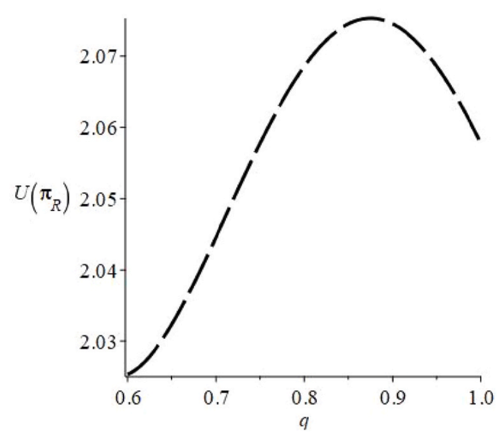


**Fig. 6.** The effect of collection quality on the retailer's profit.

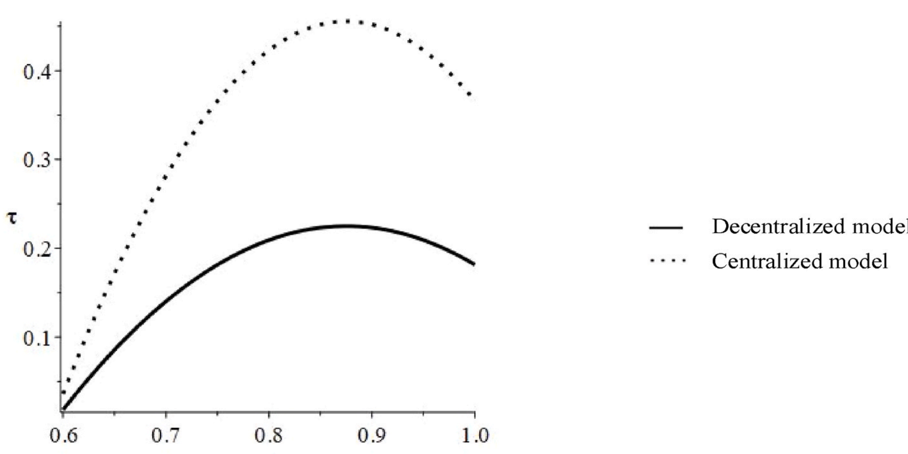


**Fig. 4.** The effect of collection quality on return rate.

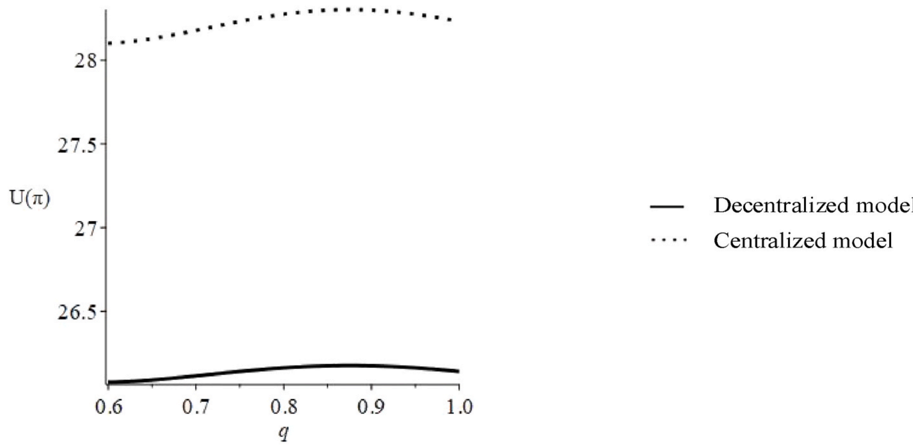


**Fig. 7.** The effect of collection quality on total profit.

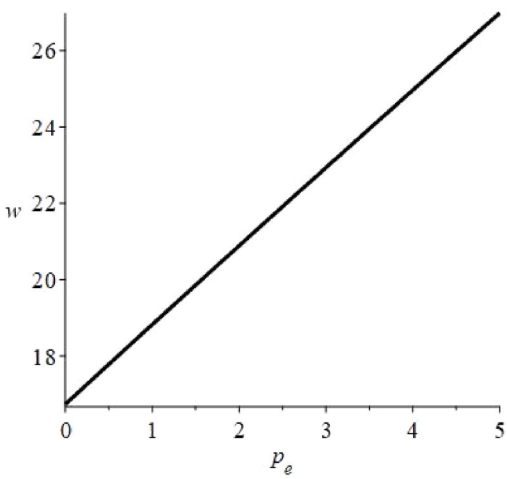


**Fig. 8.** The impact of unit carbon emission quota trading price on the unit wholesale price of EEE.

as it can help mitigate the manufacturer's risk.

However, if the collection quality exceeds this range, it is no longer profitable for the manufacturer to conduct WEEE recycling and remanufacturing as the quality level increases, leading to an increase in wholesale and retail prices to mitigate losses. It also shows that the manufacturer's risk aversion has less impact on the members' decision-making if high-quality WEEE cannot bring profits to the manufacturer.

From Fig. 4, it is evident that if $q < 0.88$, as the collection quality improves, the manufacturer with a degree of risk aversion is more inclined to collect higher-quality WEEE to achieve greater profits, which consequently leads to an increase in return rate. If $0.88 < q < 1$, conversely, the return rate decreases as the collection quality improves. This occurs because the increase in wholesale and retail prices will diminish consumer purchasing desires, leading to a reduction in the number of products available in the market, which will hinder recycling activities.

According to Figs. 5 and 6, the profits of the manufacturer and retailer increase with the increasing of WEEE collection quality within a certain threshold. However, once this threshold is surpassed, the profits for both parties will decrease. In the forward supply chain, lower retail prices for products will stimulate demand if $q < 0.88$, which will increase the volume of WEEE recycling in the reverse supply chain. Consequently, with this increase, the manufacturer gains higher profits through WEEE remanufacturing. If $0.88 < q < 1$, the market's recycling rate is low. Although the improvement of WEEE quality can reduce remanufacturing costs and carbon emissions, it also raises the unit recycling price. Furthermore, during this period, the cost savings from carbon trading, recycling, and remanufacturing are constrained, thereby diminishing profits for manufacturers engaged in WEEE recycling and remanufacturing. As a result, the gains derived from increasing the unit wholesale prices of EEE for manufacturers are limited, leading to reduced profits for both manufacturers and retailers.

It can be observed from Fig. 7 that as the collection quality increases, the total profit of the supply chain first increases and then decreases. And the total profit under the centralized model consistently exceeds that under the decentralized model. According to Figs. 2–4, under the centralized model, reduced retail prices drive an increase in market demand, consequently leading to higher profits from product sales. In addition, as the quantity of WEEE recycled rises, the expected utility from recycling and remanufacturing also increases. Hence, the total profit under the centralized model is significantly higher. In the scenario of centralized decision-making, the manufacturer and retailer align their interests. To optimize the total profit, they can collaborate transparently, aiming to eliminate inefficiencies caused by "double marginal utility".

Combining the above analysis, the heterogeneity of WEEE collection quality will exert varying degrees of impact on decisions like pricing and return rate. Hence, collection quality stands as a crucial factor that supply chain members must consider when making decisions.

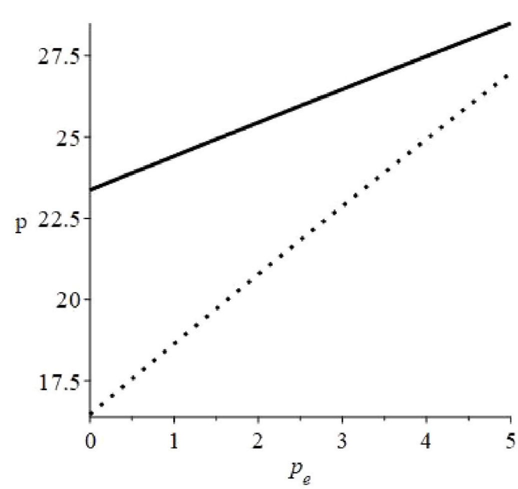


**Fig. 9.** The impact of unit carbon emission quota trading price on unit retail price of EEE.

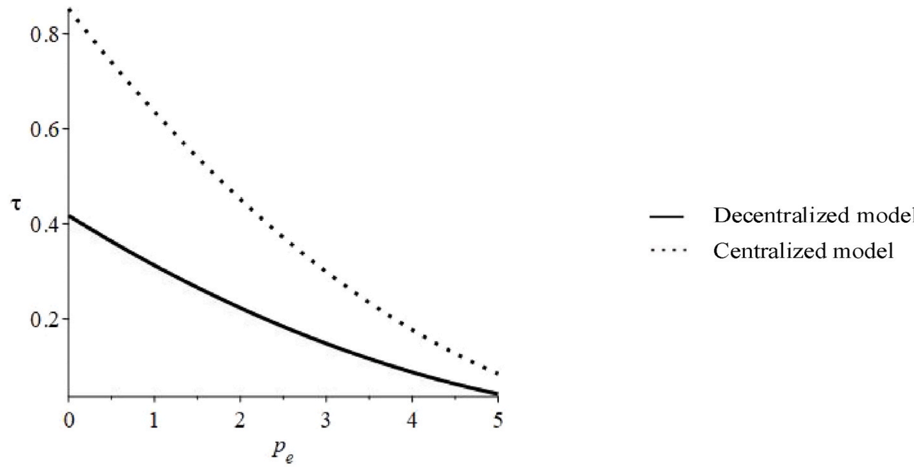


**Fig. 10.** The impact of unit carbon emission quota trading price on the return rate of WEEE.

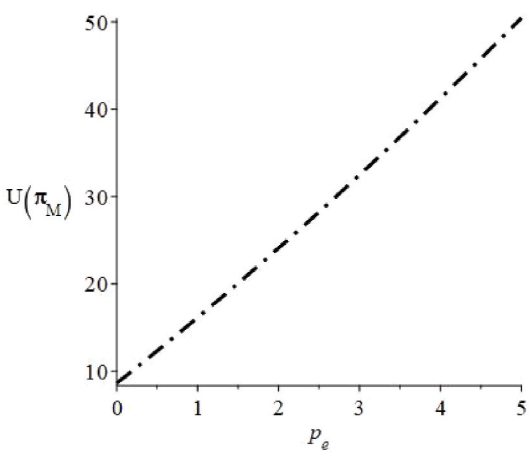


**Fig. 11.** The impact of unit carbon emission quota trading price on the manufacturer's profit.

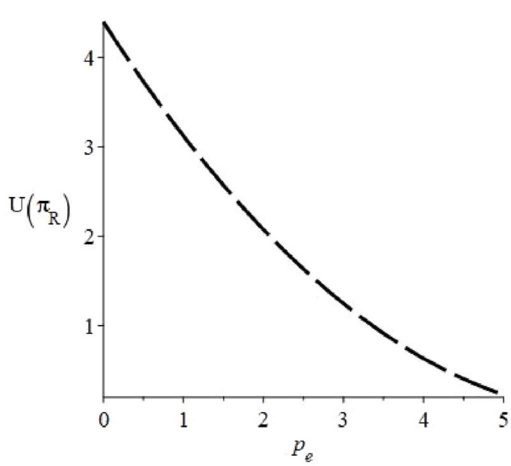


**Fig. 12.** The impact of unit carbon emission quota trading price on the retailer's profit.

### *6.1.2. The impact of the unit carbon emission quota trading price on pricing and profits*

The specific impacts of the unit carbon emission quota trading price on the return rate of WEEE, the wholesale price and retail price per unit of EEE, and profit are depicted in Figs. 8–13, assuming $q = 0.65$ at this time.

Figs. 8 and 9 demonstrate that as the unit carbon emission quota trading price increases, both the manufacturer and the retailer simultaneously raise the wholesale and retail prices per unit of EEE. This is because, as carbon emissions remain constant, the cost of purchasing carbon emission quotas increases with higher unit carbon emission quota trading price. Additionally, higher unit carbon emission quota trading price leads to increased risk aversion among manufacturers due to emission uncertainty, resulting in escalated wholesale and retail prices. Fig. 9 shows the impact of the unit carbon emission quota trading price on the unit retail price of EEE. In the centralized model, both manufacturers and retailers collaboratively determine the unit retail price of EEE, aligning their decision-making with collective interests. In this scenario, the impact of the unit carbon emission quota trading price on retail prices is relatively minimal.

The impact of the unit carbon emission quota trading price on the return rate is depicted in Fig. 10. As the unit carbon emission quota trading price increases, the return rate of WEEE diminishes. On one hand, the rise in the unit carbon emission quota trading price diminishes manufacturer profits, thereby prompting an elevation in product selling prices and a decline in market demand. However, owing to uncertainties regarding carbon emissions stemming from remanufacturing, the manufacturer leans towards decreasing the amount of WEEE to avert losses. Based on the aforementioned analysis, it can be inferred that the manufacturer decreases carbon emissions by curtailing demand and improving WEEE quality identification technologies.

Figs. 11–13 illustrate the correlation between the unit carbon emission quota trading price and supply chain member profit. From Fig. 11, with the rise in the unit carbon emission quota trading price, the manufacturer's profit rises while the retailer's decline. This is due to the manufacturer curbing carbon emissions by diminishing demand for products and lowering the return rate of WEEE, thereby reducing the transaction cost of carbon emission. It is also noted that the cost savings achieved by the reduction in carbon emissions are adequate to offset the losses incurred by increasing the unit wholesale price of EEE. Although the rise in the unit carbon emission quota trading price can effectively reduce carbon emissions, it might constrain the growth of the retailer as an increase in the unit retail price of EEE often leads to decreased demand. The increased revenue derived from raising the unit retail price of EEE is unable to compensate for the loss incurred from decreased market demand. Consequently, the retailer can collaborate with the manufacturer to share the cost of carbon trading, thereby securing a lower unit wholesale price of EEE.

Fig. 13 explores the trend of total profit as the unit carbon emission quota trading price changes. Figs. 11 and 12 depict that the manufacturer's profit escalates more significantly compared to the retailer's

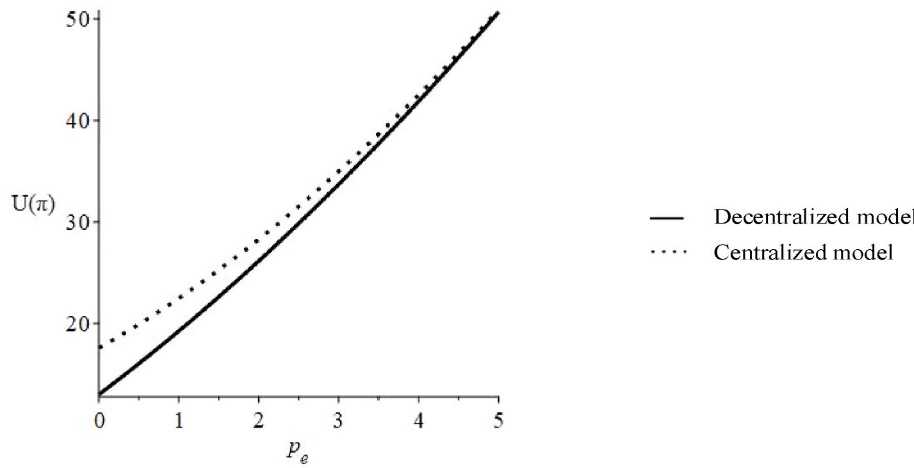


**Fig. 13.** The impact of unit carbon emission quota trading price on total profit.

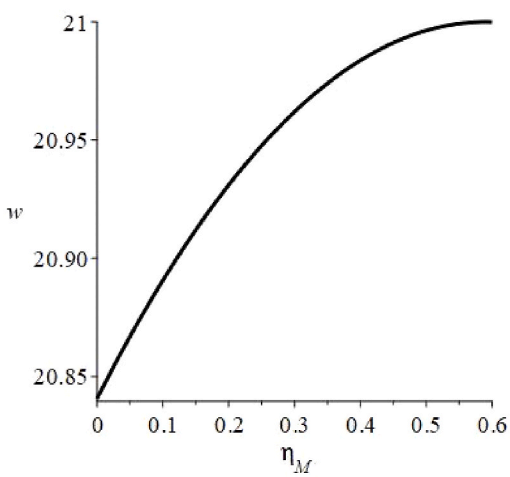


**Fig. 14.** The influence of risk aversion on the unit wholesale price of EEE.

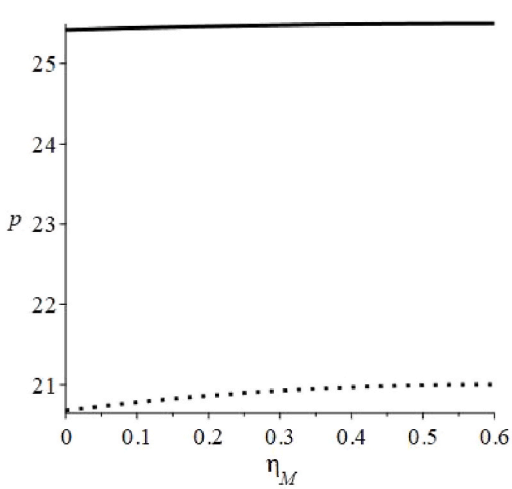


**Fig. 15.** The influence of risk aversion on the unit retail price of EEE.

decline with the rise in the unit carbon emission quota trading price, indicating that the manufacturer's profit contributes significantly to the overall profit. Therefore, the total profit correlates proportionally with the unit carbon emission quota trading price due to the manufacturer's profit increasing at a higher rate than the retailer's decreases. While the total profit under the centralized model consistently exceeds that of the decentralized model, decentralized models align more with supply chain decision-making in reality. Hence, aiming to coordinate manufacturer and retailer profits within the decentralized model, it becomes imperative to design a contract. Furthermore, this approach can attract more companies to engage in WEEE recycling, thereby facilitating the development of the remanufacturing industry.

#### *6.1.3. The impact of risk aversion on pricing and profits*

To analyze the impact of the manufacturer's risk aversion on pricing decisions, member profits, return rate, and profit of the CLSC, we conduct the numerical simulation with varying values of the risk aversion parameter.

Figs. 14 and 15 depict the effects of risk aversion on decisions of both the manufacturer and retailer. Higher levels of the manufacturer's risk aversion result in a heightened fear of profit reduction, prompting the manufacturer to incline towards raising the unit wholesale price of EEE to mitigate losses. As the leader in the CLSC, the manufacturer's decisions are followed by the retailer. Consequently, the retailer also adjusts by increasing the retail price in line with the wholesale price per unit of EEE hike.

Fig. 16 presents the return rate under different risk aversion levels. As risk aversion increases, the quantity of WEEE available for remanufacturing decreases, resulting in a decline in the return rate. This decline is attributed to the uncertainty surrounding carbon emissions from WEEE remanufacturing, which influences the manufacturer's risk attitude. To mitigate this uncertainty, the manufacturer reduces the return rate of WEEE. This indicates that the risk attitude of the manufacturer is not conducive to WEEE recycling and remanufacturing. To address manufacturers' risk aversion and enhance WEEE quality, it is recommended that the manufacturer introduce advanced technology to pretest WEEE quality and reduce detection errors. This approach can attract more companies to enter WEEE recycling and remanufacturing, consequently reducing the environmental pollution caused by WEEE.

The influence of $\eta_M$ on manufacturer's and retailer's profit is portrayed in Figs. 17 and 18. As the manufacturer's risk aversion intensifies, both the manufacturer's and retailer's profits decrease. To reduce the risks caused by the uncertainty of carbon emissions, the manufacturer tends to reduce the quantity of WEEE, consequently resulting in less revenue for the manufacturer from recycling and remanufacturing. Concurrently, the increase in retail and wholesale prices will cause reduced market demand, culminating in decreased profits for both parties. Fig. 19 highlights a decline in total profit with an increase in the manufacturer's risk aversion, where notably the total profit is higher under the centralized model. This further emphasizes the necessity of designing a contract to coordinate the profits of the manufacturer and

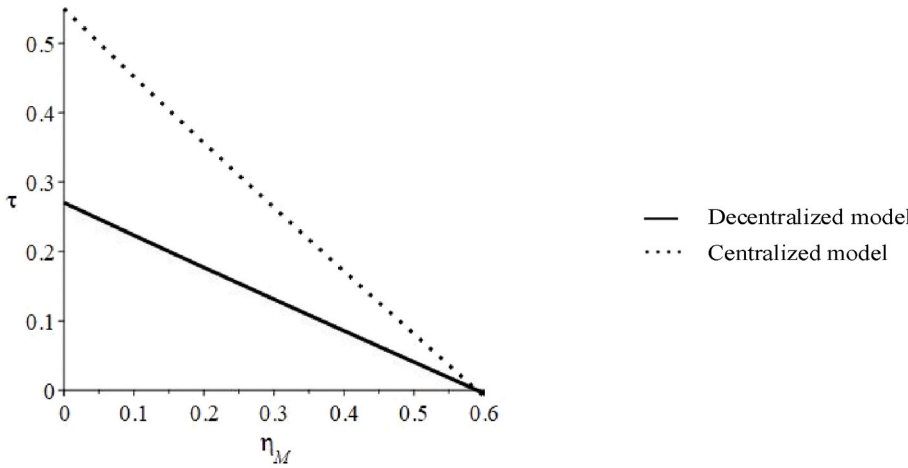


**Fig. 16.** The influence of risk aversion on return rate.

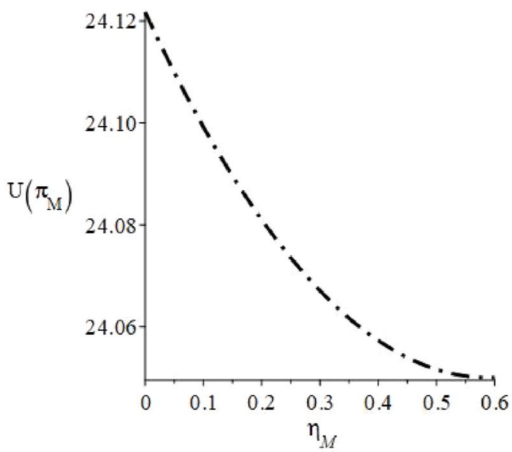


**Fig. 17.** The influence of risk aversion on the manufacturer's profit.

retailer under the decentralized model.

### 6.2. Analysis of the risk aversion and collection quality impacts on pricing and profits

To explore the combined influence of the unit carbon emission quota trading price and collection quality on optimal decision-making, we simultaneously vary their values to observe the evolving trends in the wholesale price and retail price per unit of EEE, the return rate of WEEE, and profits in this section.

The effects of $\eta_M$ and $q$ on the wholesale and retail prices of per unit EEE under the decentralized model are shown in Figs. 20 and 21. The unit wholesale price of EEE initially rises and then declines under the influence of both $\eta_M$ and $q$. When the collection quality of WEEE is low, predominantly affected by risk aversion, an exponential decrease in the unit wholesale price of EEE occurs with the rise of $\eta_M$. However, if the collection quality surpasses a threshold, it will trigger an inverse relationship between the unit wholesale price of EEE and the manufacturer's risk aversion. In this scenario, the impact of risk aversion tends to diminish due to the manufacturer's inclination to acquire high-quality WEEE. During the remanufacturing process, higher collection quality results in reduced carbon emissions, consequently lessening the impact of risk aversion on the manufacturer. Within the dominant position held by the manufacturer in the CLSC, the retailer aligns with the manufacturer's decisions. Under the combined influence of risk aversion and collection quality, the unit retail price of EEE reflects the trends observed in the unit wholesale price of EEE.

Fig. 22 illustrates the correlation between the unit retail price of EEE and various collection quality levels combined with risk aversion levels within the centralized model. When both the level of risk aversion and the level of collection quality are low, the unit retail price of EEE can reach its minimum. Moreover, a comparison with Fig. 21 reveals that the unit retail price of EEE is lower under the centralized model.

The impact of $\eta_M$ and $q$ on the return rate is depicted in Fig. 23. Simultaneous increases in collection quality and risk aversion lead to a decrease in the WEEE return rate. With the increase $q$, the return rate shows exponential growth, while an increase in $\eta_M$ results in a linear decrease in the return rate. However, the predominant shift in the return rate is primarily attributed to the manufacturer's risk aversion. The highest return rate of WEEE is observed when the risk aversion is minimal and the collection quality is higher.

Figs. 24 and 25 illustrate the impact of $\eta_M$ and $q$ on the profits of the manufacturer and retailer respectively. It is evident that when the manufacturer's risk aversion is low, an enhancement in collection quality is conducive to increasing the manufacturer's profit. However, when the manufacturer's risk aversion exceeds a certain threshold, collection quality exhibits an inverse relationship with the manufacturer's profit. At lower collection quality levels and higher manufacturer's risk aversion, the manufacturer's profit tends to increase. This is attributed to the significantly reduced return rate of WEEE, allowing the manufacturer to gain profit by lowering the unit wholesale price of EEE

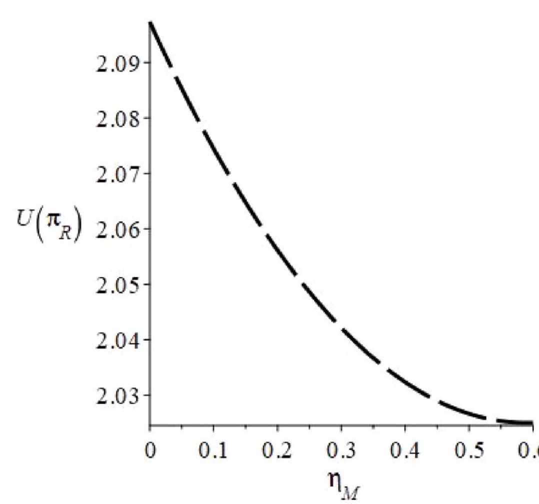


**Fig. 18.** The influence of risk aversion on the retailer's profit.

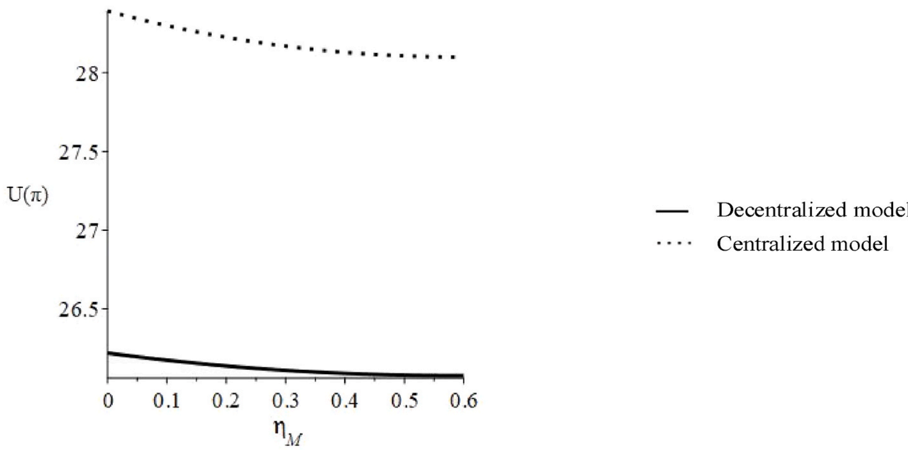


**Fig. 19.** The influence of risk aversion on total profit.

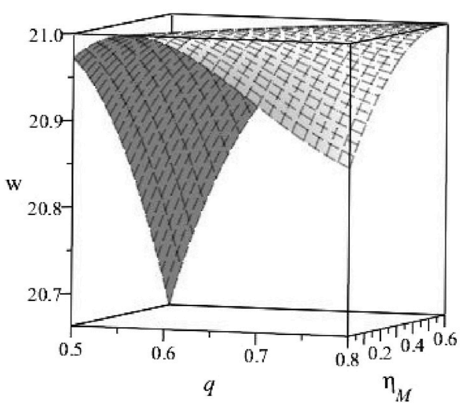


**Fig. 20.** Impact of $\eta_M$ and $q$ on wholesale price.

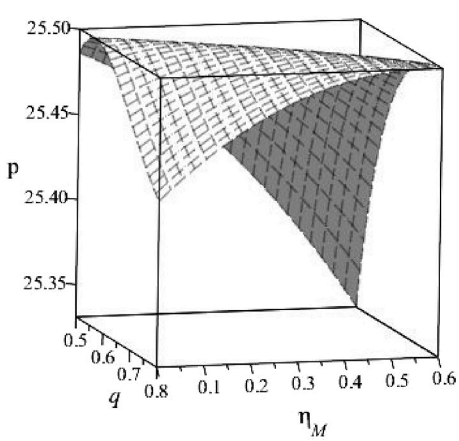


**Fig. 21.** Impact of $\eta_M$ and $q$ on the unit retail price of EEE under the decentralized model.

which surpasses the costs incurred in the recycling and remanufacturing process. The changing trend of the retailer's profit concerning $\eta_M$ and $q$ mirrors that of the manufacturer. Hence, we won't delve deeply into it.

As depicted in Fig. 25, the retailer gains more profits when collaborating with the manufacturer exhibiting high-risk aversion. Based on the above analysis, for the manufacturer, higher-quality WEEE is more advantageous when their risk aversion is low, whereas lower-quality WEEE becomes more beneficial when their risk aversion is high. Consequently, in a CLSC, both the retailer and manufacturer should consider the combined impact of $\eta_M$ and $q$.

Fig. 26 illustrates variations in the total supply chain profit across different values of $\eta_M$ and $q$. This figure distinctly indicates higher total profit under the centralized model, displaying a more pronounced trend in profit changes compared to the decentralized model. This highlights the clearer presentation of market changes within the centralized model. However, in real-world scenarios, manufacturers and retailers are more focused on how to prioritize their profit maximization, lacking a comprehensive consideration of all contributing factors comprehensively when making decisions. To foster mutual benefits and enhance cooperation among supply chain members, developing a contract for overall supply chain coordination becomes imperative.

Considering the above analysis, collection quality takes precedence in decision-making within a certain threshold. Once surpassing this threshold, risk aversion assumes a greater influence on decision-making processes. Hence, both manufacturers and retailers should holistically assess risk aversion and collection quality. For manufacturers, the quality of recycling should be strictly controlled to minimize the fluctuation of carbon emissions and remanufacturing costs and enhance the ability to withstand risks.

### *6.3. Analysis of the risk aversion and the unit carbon emission quota trading price impacts on pricing and profits*

In this section, to investigate the combined influence of risk aversion and unit carbon emission quota trading price on dynamic changes in the unit wholesale price and unit retail price of EEE, return rate of WEEE, and profits, we simultaneously adjust the values of unit carbon emission quota trading price and risk aversion.

The impacts of $\eta_M$ and $p_e$ on wholesale and retail prices are presented in Figs. 27 and 28, respectively. As both unit carbon emission quota trading price and risk aversion increase, the unit wholesale price of EEE rises. Particularly, a significant surge in the unit wholesale price of EEE is observed with an increase in the unit carbon emission quota trading price. Although an uptick in manufacturer risk aversion also leads to a rise in the unit wholesale price of EEE, its effect is less pronounced. Consequently, within the context of the dual factors $\eta_M$ and $p_e$, the unit carbon emission quota trading price exerts a more dominant influence. Throughout the operations in the CLSC, uncertainties in remanufacturing emissions contribute to the manufacturer's risk aversion. Relative to the unit carbon emission quota trading price, risk aversion demonstrates a comparatively weaker impact. The pattern of change in the unit retail price of EEE mirrors that of wholesale price, hence avoiding elaboration here. It can be seen in Fig. 28 that the unit wholesale price of EEE is higher under the decentralized model. This occurs because an increase in the unit wholesale price of EEE prompts the retailer to focus solely on their profit, consequently driving up the unit retail price of EEE.

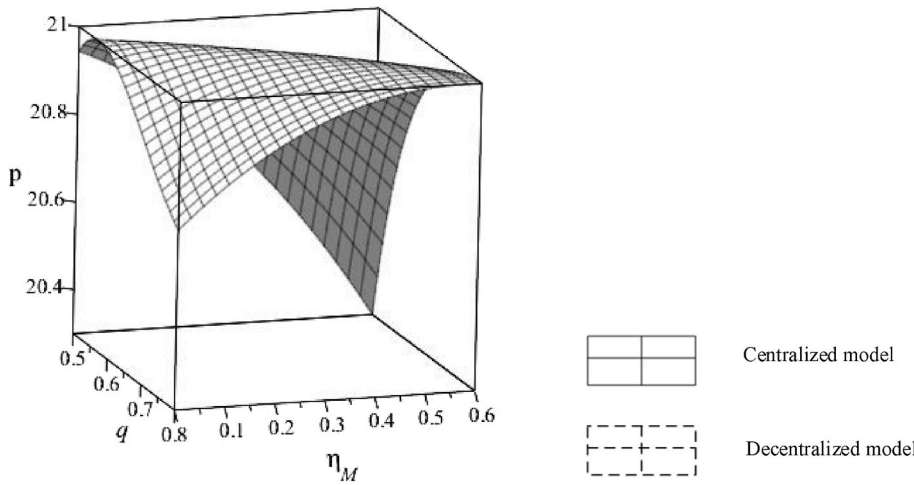


**Fig. 22.** Impact of $\eta_M$ and $q$ on the unit retail price of EEE under the centralized model.

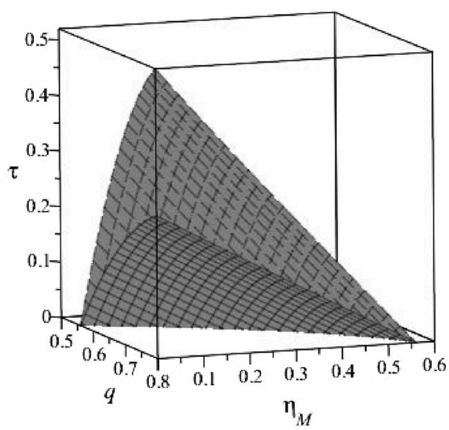


**Fig. 23.** Impact of $\eta_M$ and $q$ on the return rate of WEEE.

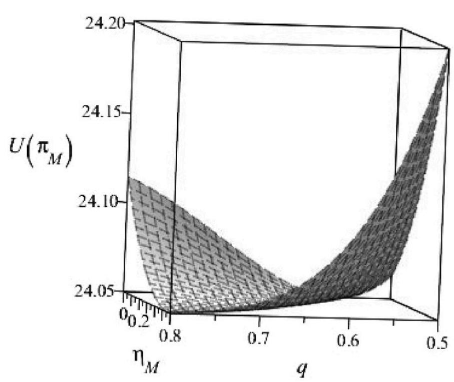


**Fig. 24.** Impact of $\eta_M$ and $q$ on the manufacturer's profit.

The impact of the unit carbon emission quota trading price and manufacturer risk aversion on the return rate is depicted in Fig. 29. Notably, an increase in the unit carbon emission quota trading price corresponds to a substantial decrease in the return rate. Similarly, heightened manufacturer risk aversion leads to a reduced return rate. Furthermore, the unit carbon emission quota trading price amplifies the influence of manufacturer risk aversion on return rates. The reason is that the increasing unit carbon emission quota trading price causes higher costs resulting from recycling and remanufacturing, which will

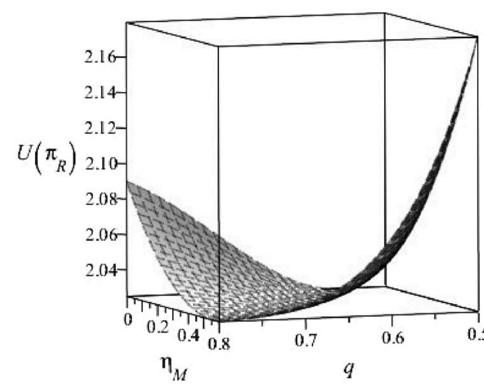


**Fig. 25.** Impact of $\eta_M$ and $q$ on the retailer's profit.

enhance the manufacturer's risk aversion. Additionally, the return rate remains consistently higher under the centralized model compared to the decentralized model. The collaborative synergy between the manufacturer and retailer significantly fosters the advancement of the recycling and remanufacturing industry, thereby mitigating the adverse environmental impact of WEEE.

Figs. 30–32 display the impacts of the manufacturer's profit, retailer's profit, and the total profit under the decentralized model concerning various unit carbon emission quota trading prices and risk aversion levels. As both the unit carbon emission quota trading price and risk aversion increase, the manufacturer's profit tends to rise while the retailer's profit declines. The retailer's decision to elevate the unit wholesale price of EEE results in a substantial reduction in market demand, which outweighs the gains from price hikes, leading to decreased profits. Under the CATR, both risk aversion and unit carbon emission quota trading price adversely affect the retailer's profit, with the unit carbon emission quota trading price exerting the greatest impact. As illustrated in Fig. 32, the total profit rises with increases in both the unit carbon emission quota trading price and risk aversion. Significantly higher total profit is noticeable under the centralized model. Total profit exhibits an upward trend in the decentralized model, primarily because the augmented profit of the manufacturer adequately offsets the reduced profit of the retailer.

### 6.4. *Effectiveness analysis of contract coordination*

This section verifies the effectiveness of RCSC. We assume that $q = 0.8$, $\eta_M = 0.5$, $p_e = 2$. Consequently, according to Section 5.2, $\varphi$ and $\xi$

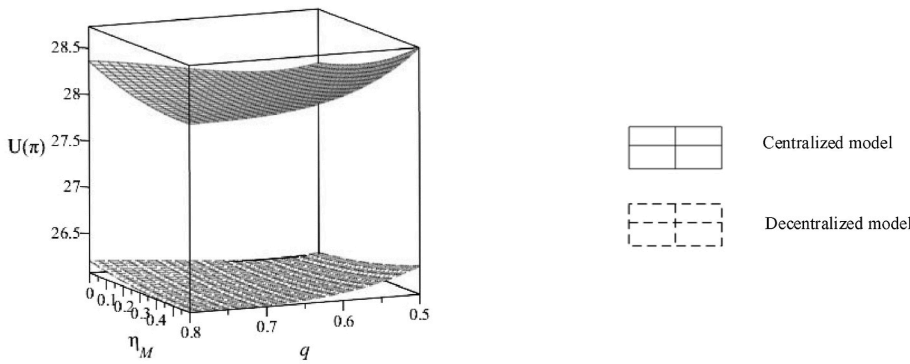


**Fig. 26.** Impact of $\eta_M$ and $q$ on total profit.

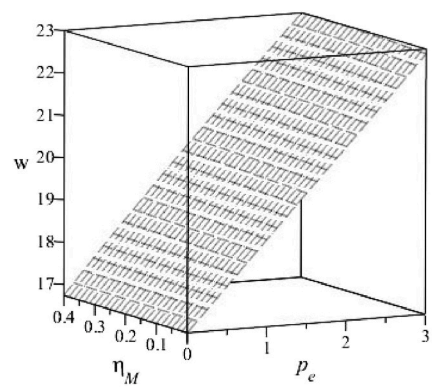


**Fig. 27.** Impact of $\eta_M$ and $p_e$ on the unit wholesale price of EEE.

are required to satisfy the following conditions: $\begin{cases} 8.1\varphi - 7.2\xi - 16 > 0 \\ 7.2\xi + 6.1 - 8.1\varphi > 0 \end{cases}$. According to the above conditions, defining $\varphi = 0.7$ and $\xi = 0.1$, the contract coordination results are shown in Table 3.

From optimal decisions in Table 3, the following conclusions can be drawn: (1) The profits of supply chain members increase by reducing the unit wholesale price of EEE and boosting the return rate within the RCSC. (2) With the coordination achieved through the contract, the total profit surpasses the pre-coordination level and reaches that of the centralized model. Hence, we can assert that the supply chain has achieved coordination through the RCSC.

Fig. 33 illustrates the range of $\xi$ and $\varphi$ when $\eta_M = 0.5$, $q = 0.8$ and $p_e = 2$. The total profit aligned with the centralized model as $\xi$ and $\varphi$ fall within the specified range is indicated in Fig. 33. This alignment ensures enhancements in both the manufacturer's and retailer's profits, encouraging their willingness to embrace the contract. This also indicates that the manufacturer and retailer will take different factors into account when designing the contract. Since the consumption preference of consumers is not considered in this paper, the prices of new products and remanufactured products are set to be the same. Both the manufacturer and retailer do not need to worry about the impact of consumer preferences on the sales of remanufactured products in the market. In such a scenario, the retailer prioritizes benefits, while the manufacturer, engaging in WEEE recycling and remanufacturing activities, focuses more on avoiding risk losses due to uncertain factors. However, if both parties solely focus on their financial inflows and outflows, it may lead to an imbalance in the supply chain. This imbalance can cause product prices to soar, subsequently reducing market demand and preventing both parties from reaching an optimal outcome in terms of their interests. The contract can regulate the level of income and expenditure of the retailer and manufacturer. In contract design, the manufacturer anticipates the retailer to shoulder a portion of the costs. To demonstrate the sincerity of cooperation and facilitate mutual goals achievement, the manufacturer also shares some of its revenue. For the manufacturer, contract formulation can help reduce their cost burden. The inclusion of contracts lowers the selling price of products in the market, accelerating product circulation WEEE recycling and remanufacturing, which further reduces manufacturers' carbon emission costs.

Figs. 34 and 35 respectively demonstrate the influence of contract parameters on the retailer's and manufacturer's profits. According to

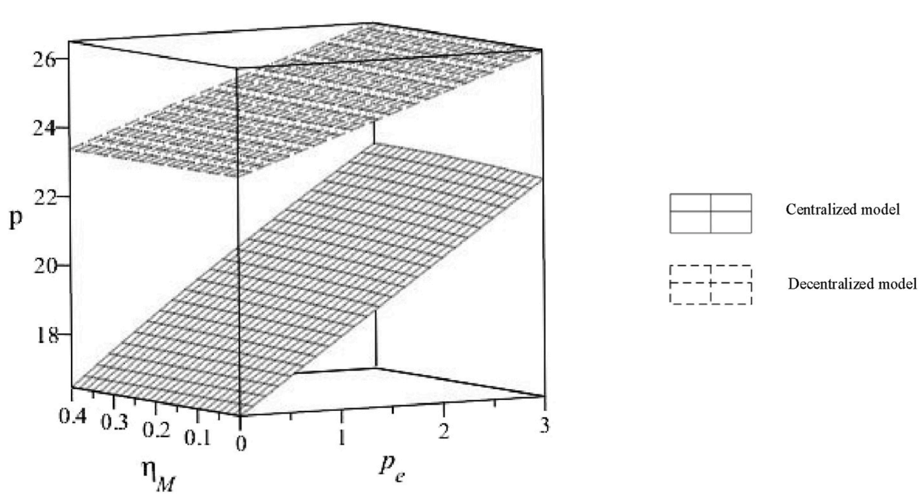


**Fig. 28.** Impact of $\eta_M$ and $p_e$ on the unit retail price of EEE.

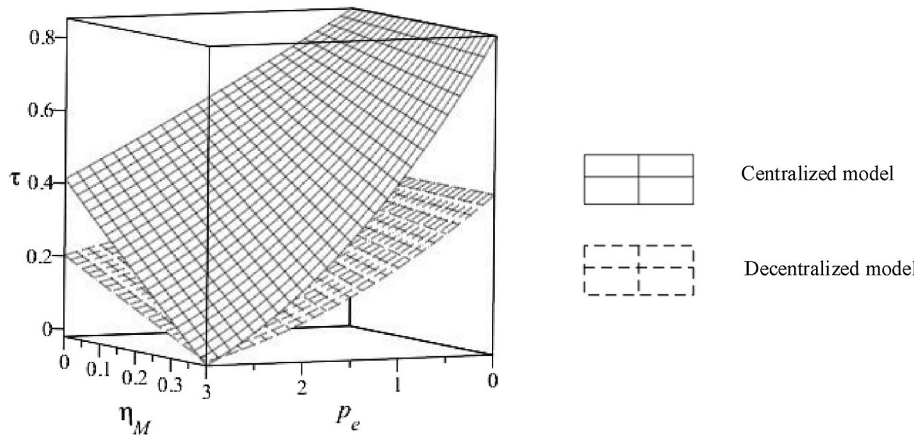


**Fig. 29.** Impact of $\eta_M$ and $p_e$ on return rate.

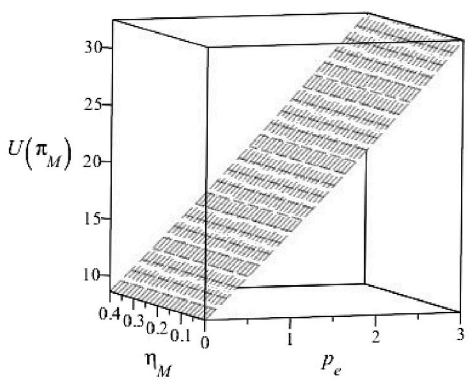


**Fig. 30.** Impact of $\eta_M$ and $p_e$ on manufacturer's profit.

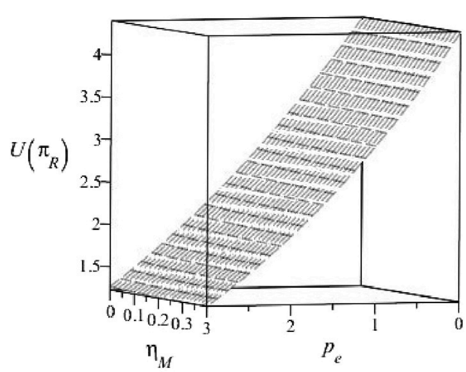


**Fig. 31.** Impact of $\eta_M$ and $p_e$ on retailer's profit.

Fig. 34, with a constant $\xi$, the retailer's profit shows an inverse relationship with $\varphi$. While $\varphi$ remains constant, the retailer profit shows an increasing tendency with the increasing of $\xi$ variable. Hence, the retailer can enhance profit by assuming a larger share of the manufacturer's carbon trading costs. Furthermore, the figure indicates that the size of $\xi$ plays a predominant role in reducing the retailer's profit. In Fig. 35, with a constant $\xi$, the manufacturer's profit shows a direct correlation with $\varphi$. However, as $\xi$ increases, while $\varphi$ remains constant, the manufacturer's profit decreases. This illustrates that augmenting the sharing proportion of revenue can notably bolster the manufacturer's profits. Additionally, it's evident that $\varphi$ holds a more substantial impact on the manufacturer's profits. Therefore, the retailer should not only aim for revenue sharing but also actively contribute to carbon trading costs. Simultaneously, the manufacturer should not solely focus on sharing carbon trading expenses but also actively partake in revenue sharing. Realistically, decisions by manufacturers and retailers should encompass a comprehensive view. Both parties should collaborate to determine a proportion that ensures a mutually beneficial outcome when crafting a contract.

## 7. Managerial implications

Remanufacturing typically involves the use of advanced processing techniques in standardized production and assembly line activities to inspect, refurbish, and restore end-of-life components to a nearly new condition, thereby reducing carbon emissions and conserving energy. WEEE contains valuable resources such as precious metals, steel, copper, aluminum, plastics, and glass, which can replace raw materials in corresponding production process. For example, Apple employs various initiatives such as the Apple Trade-In Program, the Annual iPhone Refresh Program, and the Apple Employee Device Reuse Program to collect and refurbish EOL devices. In 2019, twenty-eight percent of the aluminum used in Apple's manufacturing processes was sourced from recycled materials (Kan and Miller, 2022). When a device becomes inoperable as a whole, Apple prioritizes the quality of recycled products by focusing on the recycling and reuse of parts that are still functional. These components undergo refurbishment and rigorous testing to meet quality standards before being reused as replacement parts for equipment maintenance. Additionally, to minimize secondary part destruction and avert losses due to quality issues during disassembly, Apple also introduced the iPhone disassembly robot Daisy into the remanufacturing process, which can dismantle 15 different iPhone models into various independent parts. Compared to those obtained through conventional recycling techniques, recycling facilities can then recover more high-quality important materials. The recycling and remanufacturing of WEEE ensure the continued functionality of high-quality parts while simultaneously reducing the necessity for manufacturing new spare parts.

Combining the aforementioned case and our research model, this study provides significant contributions to the existing literature on carbon emission reduction and valuable insights for manufacturers and retailers engaged in recycling and remanufacturing practices. The managerial implications are given below.

(1) This paper offers a valuable decision-making reference for participants involved in WEEE recycling and remanufacturing, supporting their active contribution to achieving carbon neutrality goals. Variations in WEEE quality primarily impact the optimal recycling quantity and the profitability of participants. The manufacturers can conduct a quality pre-test on the WEEE before engaging in remanufacturing, thereby reducing losses caused by the heterogeneity of WEEE quality. This has helped attract more

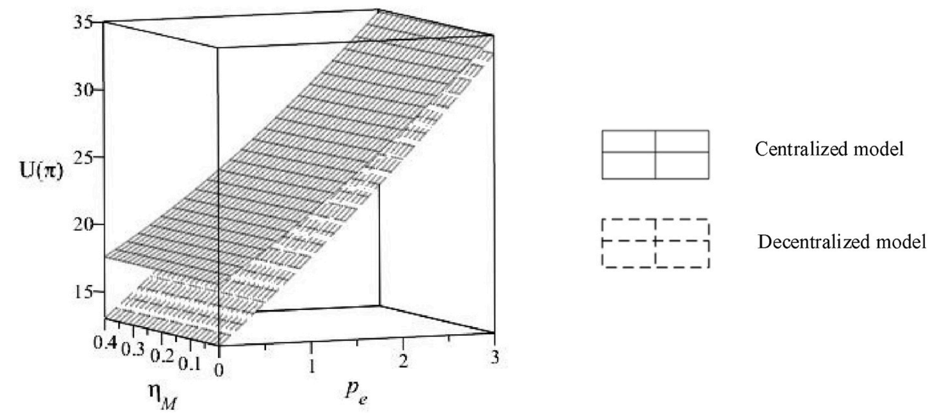


**Fig. 32.** Impact of $\eta_M$ and $p_e$ on total profit.

**Table 3**
Optimal decisions under RCSC.

| Parameters | Decentralized model | Centralized model | RCSC |
|---|---|---|---|
| $p$ | 25.5 | 21 | 21 |
| $\tau$ | 0.03 | 0.05 | 0.05 |
| $w$ | 21 | – | 4 |
| $\pi_M$ | 24.1 | – | 24.9 |
| $\pi_R$ | 2 | – | 3.2 |
| $\pi_M + \pi_R$ | 26.1 | 28.1 | 28.1 |

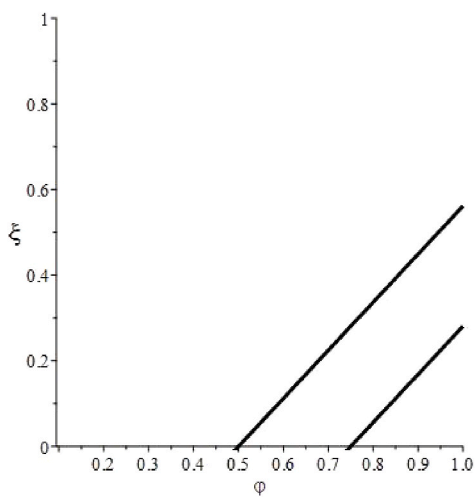


**Fig. 33.** The value range of $\xi$ and $\varphi$.

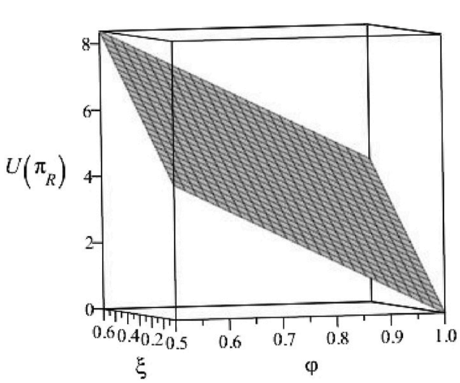


**Fig. 34.** Impact of $\xi$ and $\varphi$ on retailer's profit.

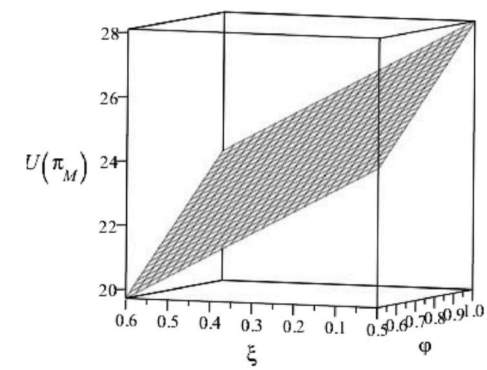


**Fig. 35.** Impact of $\xi$ and $\varphi$ on manufacturer's profit.

companies into the field of recycling and remanufacturing of WEEE quality, finally curb the environmental pollution of scrapped electronic and electrical equipment.

(2) Considering the risk aversion of manufacturers stemming from the quality heterogeneity of WEEE under the CATR, this paper provides an introductory guidance that better aligns with the psychology of decision-makers and the realities of remanufacturing. The risk aversion of manufacturers can reduce the profits of supply chain members, which in turn may diminish their enthusiasm for WEEE recycling and impede the growth of the recycling and remanufacturing sector. To address this issue, the government could set a minimum return rate of WEEE, imposing penalties on manufacturers who fail to meet this recycling threshold. Such measures would not only facilitate the monitoring of manufacturers' recycling efforts but also enhance their motivation for engaging in WEEE recycling.

(3) This study demonstrates that contract positively influences decision-making among participants in CLSC. In WEEE remanufacturing activities, members, particularly manufacturers, need to weigh both recycling quality and risk aversion in their decision-making processes. The government should enhance public awareness of WEEE recycling through educational campaigns, marketing strategies, and incentive programs, encouraging timely engagement in WEEE remanufacturing. This initiative aims to reduce manufacturers' risk aversion and encourage more companies to enter the WEEE remanufacturing sector, ultimately curbing the environmental pollution stemming from WEEE. Additionally, it is recommended that the government implement recycling subsidies to stimulate manufacturers' enthusiasm for collecting high-quality WEEE.

## 8. Conclusions

Considering the uncertainties in carbon emissions due to the heterogeneity quality of WEEE, which in turn triggers a risk-averse stance of the manufacturer in decision-making, this study formulates a CLSC composed of a risk-averse manufacturer and a risk-neutral retailer. Drawing from the analysis of pricing and return rate decisions in both decentralized and centralized models, it introduces an RCSC as a means of coordinating the supply chain. Subsequently, a numerical simulation is employed to analyze the impact of the unit carbon emission quota trading price, collection quality and manufacturer risk aversion parameters on decisions regarding pricing and return rates. The primary conclusions drawn are as follows.

(1) This paper simultaneously considers the joint impact of quality heterogeneity and risk aversion on the decision-making of CLSC members under the CATR. It is found that the unit carbon emission quota trading price correlates directly with both wholesale and retail prices. As the price of the unit carbon emission quota increases, it intensifies the manufacturer's risk aversion, leading to an increase in wholesale prices to mitigate potential losses, which in turn raises the retail price. Under the combined influence of the unit carbon emission quota trading price and risk aversion, the return rate decreases, as the trading price further amplifies the effect of the manufacturer's risk aversion on this rate. Simultaneously, both collection quality and risk aversion contribute to a decrease in the WEEE return rate.
(2) Comparing the decision-making behaviors of members in scenarios with and without manufacturer risk aversion, we found that the risk aversion not only diminishes the manufacturer's profits but also impacts the retailer's revenue. In contrast to scenarios without risk aversion, higher manufacturer risk aversion amplifies wholesale and retail prices while reducing the return rate. This reluctance toward risk inhibits manufacturers' enthusiasm for recycling and hampers the growth of the recycling and remanufacturing sector.
(3) The impact of WEEE collection quality on supply chain decisions decreases when the manufacturer's risk aversion is considered. This is mainly due to the collection quality of WEEE affects carbon emissions, while the risk aversion characteristic is to reduce the losses caused by carbon emissions, thereby risk aversion can reduce the impact of the quality. To elevate the WEEE recycling rates and mitigate environmental pollution, a subsidy strategy could be implemented to empower manufacturers in risk management.
(4) Aiming to supplement the pricing and coordination decision-making of CLSC under carbon cap-and-trade, this paper considers carbon trading and risk aversion cost sharing when formulating a contract. In RSCS, retailers can increase their profits by sharing a larger proportion of the carbon trading and risk costs, while manufacturers can obtain more profits as the revenue-sharing proportion increases. Hence, manufacturers and retailers should collaborate to establish a contract ratio, aiming for a mutually beneficial situation.

However, this paper still has limitations in terms of research content. Future studies could be expanded in the following directions.

(1) In practice scenarios, consumer preferences for remanufactured products influence product pricing, often leading companies to offer remanufactured items at discounted prices compared to new ones. However, this study overlooked consumer perception in its analysis of the factors affecting product pricing. Future research could explore the impact of consumer preferences on product pricing decisions under the CATR. When setting prices for remanufactured and new products, it may be beneficial to utilize consumer preference coefficients to establish retail and wholesale prices.
(2) This paper assumes that the manufacturer exhibits risk-averse behavior due to the uncertainty of carbon emissions. However, when collaborating with risk-averse manufacturers, retailers also adopt a risk-averse attitude. Moreover, the varying degrees of consumer acceptance of remanufactured products affect retailers' procurement and sales of these items, which is also a significant influencing factor on retailers' risk-averse attitudes. Future research could consider both manufacturers and retailers as risk-averse entities, discussing the impact of different risk-aversion coefficients on product pricing and contract decisions.
(3) The carbon emissions studied in this paper only pertain to production, which ignores accounting for emissions generated during transportation, dismantling, and other stages. Future research could delineate the carbon emissions generated during the processing of remanufactured products, such as dismantling and cleaning stage. These emissions could be considered in the total carbon emissions of the CLSC, enabling a more detailed exploration of the impact of WEEE quality heterogeneity on pricing and coordination decisions within the CLSC.
(4) This paper focuses primarily on the effects of collection quality of WEEE, carbon trading price, and risk aversion. However, it does not account for other important factors such as regulatory requirements or technological advancements. In future research, other strategic decision-making issues related to governmental carbon regulatory activities and technological improvement can be addressed by formulating new models in new industrial scenarios.

## CRediT authorship contribution statement

**Fuli Zhou:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Conceptualization. **Chenchen Zhang:** Writing – original draft, Methodology, Data curation. **Sunil Tiwari:** Writing – review & editing, Supervision, Data curation, Conceptualization. **Xingjun Huang:** Writing – review & editing, Visualization, Conceptualization. **Saurabh Pratap:** Software, Resources, Investigation.

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## Data availability

Data will be made available on request.

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