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EXPAND OR NOT? TRADE-OFFS OF THE REMANUFACTURER ON RECYCLING CHANNELS

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Abstract. The integration of online trading has emerged as a crucial driver of operational efficiency in the reverse supply chain. This study expands the recycling model to include three distinct scenarios: basic-offline recycling (BR), single-platform recycling (SR), and dual-platform recycling (DR). The research delves into the implications of varying platform numbers, profit-sharing contracts, consumer recycling preferences, and recycling price adjustment speeds on supply chain stability within a multi-period decision-making framework. Findings reveal that the SR model is not always yield higher profits for remanufacturers through lower revenue allocation proportions to platforms, in stark contrast to the DR model. Furthermore, rapid decision adjustments do not consistently enhance the stability of the recycling system across multiple decision cycles. Remanufacturers' expansion strategies are significantly impacted by the costs associated with acquiring e-waste from individual recyclers. Importantly, an excess of platforms does not always result in favorable outcomes. Conversely, the SR model proves superior to the DR model in practical contexts that may arise. These insights offer valuable guidance to remanufacturers seeking to develop viable expansion strategies that foster mutually beneficial relationships among individual recyclers, remanufacturers, and platforms.

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1. Introduction

The effectiveness of the offline recycling supply chain has been significantly impacted in recent years by the escalating severity of various social emergencies, such as pandemics. Taking the e-waste reverse supply chain as a case in point, remanufacturers are receiving a diminishing amount of e-waste from offline individual recyclers. Obtaining information about the recycling and remanufacturing needs of dispersed individuals has become extremely challenging, thereby severely hindering the recycling process. Unlike traditional supply chains, the reverse supply chain remanufacturing model facilitates the transfer of end-of-life products, reduces production costs and raw material consumption, enhances environmental sustainability, and generates economic benefits [1, 2]. Abandoned electronic devices serve as a specific type of raw material for remanufacturing. With the rapid growth of the Chinese economy and the improved living standards of residents, electronic equipment is increasingly prevalent in households and workplaces. In 2021, China's electronics manufacturing sector saw a 15.7% increase in added value compared to the previous year. Mobile phones, constituting a significant portion

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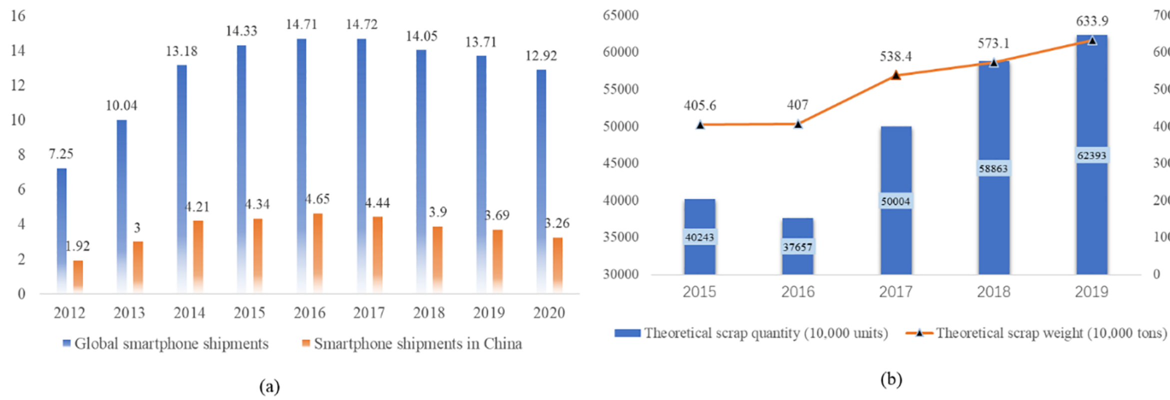

FIGURE 1. The E-waste growth trends of the world and China. (a) Global and China smartphone shipments from 2011 to 2020 (100 million). Source: IDC Prospective Industry Research Institute. (b) Theoretical scrap quantity of discarded electrical and electronic products in China (ten thousand units/ten thousand tons). Source: China Household Appliances Research Institute & Prospective Industry Research Institute.

of the main products, were produced at a steady annual growth rate, as depicted in Figure 1a. As technological advancements lead to quicker replacements of electronic equipment, these devices reach their peak scrap value. Metal-rich electronic devices are both a product of resources and the environment. Improper disposal can result in the generation of hazardous substances [3], turning a large number of electronic devices into disregarded electronic waste that poses a potential environmental threat. The decline in e-waste recycling efficiency through offline channels has led to an accumulation of e-waste stock, leading to substantial resource wastage. Global e-waste production peaked at 53.6 million tons in 2019 and is projected to reach 74.7 million tons by 2030 [4], underscoring the significance of e-waste disposal as a global resource and environmental concern. The e-waste situation in China is particularly concerning. Data from China's Forward-looking Industry Research Institute reveals a continuous increase in the theoretical scrap quantity of abandoned electrical appliances and electronic products since 2015. In 2019, theoretically, 623.93 million units of 14 different outdated electrical and electronic products were scrapped. The recycling industry faces challenges due to the substantial stock and increment, as illustrated in Figure 1b, with the theoretical scrap weight estimated at 6 339 200 tons [5]. The indiscriminate waste disposal practices have exacerbated environmental protection and resource reuse challenges, necessitating more effective approaches to address waste recycling, treatment, and remanufacturing management issues. This calls for the promotion of the circular economy and sustainable development to combat the severity of environmental issues and resource depletion.

In recent years, there has been a notable increase in research on recycling, green practices, and sustainable supply chain management. Scholars have made significant contributions to waste resource utilization and green supply chain management from various perspectives. Taleizadeh *et al.* explored consumer preferences for new *versus* refurbished products in a closed-loop multi-tier supply chain, shedding light on consumer inclinations towards sustainable products and the potential for product reuse [6]. This study is instrumental in understanding consumer behavior towards sustainable products and exploring opportunities for product reutilization. Sarkar and Guchhait delved into the impact of information asymmetry on green supply chain management, encompassing aspects such as carbon trading, services, and supplier inventory management strategies. Their work underscores the critical role of information symmetry in ensuring the sustainability of supply chains [7]. Ullah *et al.* concentrated on the significance of remanufacturing in a three-tier closed-loop supply chain for waste management, emphasizing the pivotal role of remanufacturing in fostering sustainable development [8]. Dey *et al.* investigated the implications of carbon policies and multi-period payment delays in a global supply chain context, with a focus on remanufacturing [9]. Ho and Sarkar's research centered on reducing carbon emissions and propelling the sustainable development of green supply chains through multi-stage intelligent biofuel production [10]. Collectively, these studies offer valuable insights into recycling supply chain management, emphasizing specific factors influencing green supply chain practices such as consumer preferences for new *versus* refurbished products, information asymmetry issues, carbon emissions and policies, and other environmental considerations. The studies also provide management insights aimed at enhancing sustainability practices within supply chains.

Unlike previous studies, this research focuses on how business layout and partnerships impact reverse supply chain management and proposes better strategies for expanding recycling channels. In offline recycling modes, remanufacturers typically act as upstream enterprises, obtaining recycled products from recyclers rather than consumers [11, 12], leading to a lack of control over the recycling process [13, 14]. With the advent of the Internet, the recycling industry now has more options. An increasing number of remanufacturers are opting to establish direct recycling channels [15, 16] to mitigate risks associated with emergencies arising from the development of online platforms [17]. Remanufacturers are creating online recycling channels through various collaboration modes [18]. While some companies establish their independent recycling channels like Apple's Trade-in program, directly engaging with consumers through their official website to exchange old products for new ones, achieving a win–win situation, in most cases, remanufacturers choose to partner with recycling platforms to leverage existing platforms for developing their online recycling channels due to the time and cost involved in building a recycling channel [19–21]. For example, in 2019, "Huawei" collaborated with "JD.com" and "AIHUISHOU[1]" to introduce the "Trade in theme day", encompassing a broader range of products and brands. As the online platform functions as a separate entity [22], it becomes challenging for remanufacturers to lead such collaborations [23]. The structural models of the supply chain significantly impact the interests of enterprises, providing valuable insights for enterprise decision-making. Hence, when expanding direct recycling channels, remanufacturers often select multiple platforms as trading mediums with consumers. The choice of the intermediary platform and collaboration mode influences their interests [24].

Recent studies have explored the impact of supply chain structure on enterprise profits and decision-making from various angles. Hong *et al.* examined the influence of information sharing quality on competition under different channel structures, particularly comparing public and private information in diverse channel structures [25]. Zheng *et al.* discussed optimal investment in corporate social responsibility within a closed-loop recycling supply chain, considering how supply chain structure impacts decision-making, offering guidance to corporations on social responsibility [26]. Tao *et al.* delved into optimal channel structure design for a green supply chain concerning consumer demand for environmental awareness [27]. Lu and Menezes focused on the impact of supply chain vertical competition and product diversification under various supply chain structures, emphasizing the influence of supply chain structure on competitive behavior [28]. Li and Wang studied the effects of supply chains with different power structures under carbon tax policies on enterprise pricing strategies and social welfare [29]. Previous research on supply chain structure management has primarily concentrated on traditional sales supply chains, with limited exploration of reverse supply chains.

Differing from previous studies, this research proposes that remanufacturers implement a benefit-sharing system, allocating income from online channels to platforms in proportion. This creates a new cooperative model rather than maintaining a traditional upstream-downstream independent structure. The innovative recycling structure deviates from the conventional dual-channel reverse supply chain. Notably, the online channel is primarily controlled by the upstream remanufacturer rather than the traditional online recycler. The dynamic between remanufacturers and offline individual recyclers transcends a simple upstream-downstream relationship or a competitive dynamic between online recycling platforms and individual recyclers [11]. Remanufacturers are expanding their business models within the recycling process, positioning themselves as both the upstream enterprise for individual recyclers and competitors at the same level. They directly capture the market share of consumers who prefer online recycling channels through collaborations with recycling platforms while also engaging in e-waste collection from individual recyclers. This dual role intensifies competition in the reverse

[1]It's a part of ATRENEW, positioned as an "Internet + environmental protection" circular economy enterprise, dedicated to becoming a model ESG enterprise by incorporating social responsibility into business operations.

supply chain, magnifying associated risks such as profit fluctuations and potential losses. The evolving business model of recycling channels has introduced significant changes, though the precise mechanisms remain unclear, rendering the competitive landscape more intricate [30]. Remanufacturers strategically optimize operational benefits by adjusting the profit distribution structure to assert complete control over online recycling channels, encouraging online platforms to proactively enhance recycling influence [15]. An essential consideration lies in how the remanufacturer's selection and decision-making regarding online recycling platforms impact profitability and the pursuit of greater benefits. This study offers insights by analyzing and contrasting remanufacturers' profit variations across different decision combinations in offline recycling (BR), single-platform recycling (SR), and dual-platform recycling (DR). It aims to solve the following problems:

(1) How does the decision on the revenue allocation proportion to platforms affect the remanufacturer's profit and stability? How can remanufacturers rationally design coordination mechanisms to gain more from expanding online recycling channels?
(2) How does consumers' preference for recycling channels affect the remanufacturer's profit? What guidance strategies are available?
(3) When comparing the effects of the remanufacturer's expansion of the recycling structure through a single *versus* dual platform, which business mode is more beneficial to the development of the remanufacturer?

To address the aforementioned inquiries, this paper integrates the revenue allocation proportion from the remanufacturer to platforms and consumers' recycling preferences into models. It explores how market conditions impact the remanufacturer's profit across different modes and derives insightful conclusions. This study makes three key contributions. Firstly, it examines the interactive effects of revenue allocation proportion, consumer recycling preferences, and the remanufacturer's recycling costs from individual recyclers on profits within the BR, SR, and DR models. Unlike in the DR model, allocating less revenue to the platform does not necessarily lead to higher profits for the remanufacturer in the SR model. Moreover, the decision of whether remanufacturers should expand online recycling channels is directly linked to the costs incurred in acquiring e-waste from individual recyclers. Secondly, the paper investigates the impact of the speed of enterprise decision adjustments on business earnings and system stability within the SR model over multiple decision-making cycles. It reveals that excessively rapid decision adjustment by enterprises can jeopardize supply chain system stability. Only by maintaining decision adjustment speeds within a specific range can system stability be preserved. Lastly, the study compares the remanufacturer's profits across the three models under varying parameter combinations. The research finds that the DR model outperforms the SR model only when the remanufacturer provides unlimited profits to individual recyclers, a scenario that is highly improbable. This insight offers guidance for enhancing the structure of remanufacturers' businesses to prevent resource over-allocation waste and enhance management efficiency.

The subsequent sections of this article are organized as follows: Section 2 reviews pertinent literature. Section 3 outlines the basic reverse supply chain (BR) model. Section 4 delves into the complexities of system dynamics and stability strategies based on the established single platform (SR) model. Additionally, this section considers the fluctuations in remanufacturer profits due to changes in contract parameters and consumer preferences, analyzing this phenomenon's mechanism through supply chain management practices and numerical simulations. In Section 5, a dual platform (DR) model controlled by the remanufacturer is introduced, examining the impact of revenue allocation proportion and consumer recycling preferences on remanufacturer profits. Section 6 compares the three models and presents strategic recommendations for remanufacturers, while Section 7 summarizes the research findings. The solving processes of the models are detailed in the appendix.

2. Literature review

This work builds on and contributes to the literature stream of supply chain structure and reverse supply chain coordination. We subsequently review the extant literature briefly and discuss the essence of our work.

2.1. Supply chain structure

The supply chain structure in this study is mainly based on the literature on reverse supply chain, which is divided into two channel structures: recycling by individual recyclers and recycling by online platforms operated by remanufacturers. In the traditional reverse supply chain, only offline recyclers have direct contact with consumers, and upstream remanufacturers have difficulty in getting direct contact with customers [31]. This status quo makes it difficult for upstream remanufacturers to obtain the most intuitive information about consumer preferences and demands [32]. As a result, more upstream remanufacturers are opening up online recycling channels for direct recycling, which is similar to the development of direct sales channels in the forward supply chain [33, 34]. As remanufacturers need to invest more resources to build their own channels, the implementation cycle is long and the cost is difficult to estimate, only large-scale remanufacturers can build their own recycling channels [35]. Therefore, most remanufacturers choose to recycle by third party platforms. They still cannot establish the connection with consumers essentially in this way [36]. This study differs from the previous dual-channel supply chain research. The online recycling channel expanding by remanufacturers in this paper promote a win–win partnership through revenue sharing contracts with third-party platforms. In this structure, the remanufacturer is not only an upstream company, but also a competitor of other recyclers. In other studies related to supply chain coordination, Liu *et al.* incorporate suppliers' effort performance levels and fair concern behavior into the supply chain model to achieve long-term relationships between retailers and multiple suppliers through cost-sharing mechanisms [37]. Saha uses two pricing approaches: consistent pricing under the traditional retail channel and differentiated pricing under the vendor-direct channel. The results show that dual channels outperform single channels under certain conditions, and thus he proposes a coordination mechanism for the dual channel case [38]. On this basis, his team went on to study the impact of government subsidy behavior on a dual-channel closed-loop supply chain pricing strategy, and analyzed the changes in profits before and after government subsidies [39]. Heydari *et al.* analyzed the synergistic effects of different incentives (tax-free subsidies) on closed-loop supply chains and found that the government prefers incentives for manufacturers over retailers [40]. Other studies considered consumer sensitivity to green products, constructed a game model under revenue sharing contracts, quantitatively analyzed the impact of contracts on pricing decisions, and coordinated the supply chain [41]. The above studies focus on the changes and optimization strategies brought by the addition or change of key parameters to the supply chain system in a traditional two-channel reverse supply chain or a forward supply chain involving channel invasion. The research in this paper complements the model of firm cooperation in reverse supply chains by exploring the changes brought about by firm decisions for cooperation performance and their coping strategies in the presence of remanufacturer-to-recycling channel invasion.

2.2. Reverse supply chain coordination

The economic and social implications arising from electronic waste have attracted increasing attention from various sectors of society and academia. Effective recycling of electronic waste is crucial to addressing the issue, and recycling needs to be achieved through a reverse supply chain. The field of reverse supply chain, which has existed for over 20 years, has been extensively studied by scholars regarding factors such as differences and conflicts between various channels in the reverse supply chain network design [42], cooperative relationships [43], pricing strategies [44, 45], and contract design [40]. Among these, pricing for recycling not only affects the upstream-downstream relationships in the supply chain, consumer willingness to recycle, and the amount of recycling, but also impacts the unit operational maintenance profit of recycling enterprises [46]. Feng explored pricing strategies under three models: offline single-line recycling channels, single-line recycling channels under the guidance of recycling centers, and dual-line recycling channels, pointing out that dual-line recycling channels can maximize the benefits of both the recycling center and the entire system [47]. Furthermore, Feng constructed a benefit-sharing contract for dual-line recycling channels based on consumer preferences to coordinate supply chain partner relationships. Giri analyzed the pricing and return decisions of a dual-channel reverse supply chain under five different channel power scenarios: centralized, decentralized, manufacturer-led, retailer-led, and

Table 1. Contributions of different authors.

Author(s)	Structure comparison	Dual-channel	Recycling or remanufacturing	Strategy
Hong *et al.* [25], Tao *et al.* [27] and Lu *et al.* [28]	√			
Shi *et al.* [22] and Wang *et al.* [35]		√		
Ho *et al.* [10], Wang *et al.* [23], Gupta *et al.* [30], Nnorom *et al.* [46], He *et al.* [49] and Guo *et al.* [43]			√	
Huang *et al.* [32], Chen *et al.* [16], Cai *et al.* [17], Sarkar *et al.* [7], Avinadav *et al.* [24], Song *et al.* [41] and Yoo *et al.* [44]				√
Li *et al.* [11] and Saha *et al.* [39]		√	√	
Dey *et al.* [9], Qin *et al.* [13], Fang *et al.* [20], Zhang *et al.* [36], Heydari *et al.* [40], Govindan *et al.* [42], Zheng *et al.* [45], Feng *et al.* [47] and Zheng *et al.* [50]			√	√
Kushwaha *et al.* [14] and Huang *et al.* [18]	√		√	
Zheng *et al.* [26], Li *et al.* [29] and Liu *et al.* [51]	√			√
Qi *et al.* [21] and Ha *et al.* [31]		√		√
Saha [39]	√	√		√
Taleizadeh *et al.* [6], Ullah *et al.* [8], Liu *et al.* [12], Ma *et al.* [15], Farouk *et al.* [19], Yuan *et al.* [52] and Giri *et al.* [48]		√	√	√
This paper	√	√	√	√

third-party-led [48]. Through numerical analysis, he concluded that the retailer-led approach could bring higher returns to the supply chain. By proposing contract and authorization mechanisms to coordinate the subject relationships under decentralized decision making, it was found that contract coordination can achieve optimal recovery rates compared to authorization mechanisms [49]. Zheng *et al.* proposed three coordination mechanisms based on Shapley value, kernel solution, and equal satisfaction to optimize a three-level closed-loop supply chain consisting of manufacturers, distributors, and fair-conscious retailers. The study helped managers understand how to promote cooperation and achieve equitable distribution of surplus profits [50].

Table 1 shows the contributions of different authors. This work is also relevant to reverse supply chain strategies, but differs from the previous literature in the following ways. Firstly, this study considers the relationship between consumers' preference of online channels and remanufacturers' profits, and illustrates changes of the remanufacturer's profit before and after the expansion of online channels. It can largely determine whether it is necessary for remanufacturers to expand online recycling channels. Secondly, the dual-channel reverse supply chain explored in this study is somewhat different from the previous studies. Most previous studies maintain the relationship between the remanufacturer and the platform through fixed-fee contract or allocating a certain proportion of income to the recycling platform based on the cash flow. In addition, this study compares the difference between single-platform and dual-platform recycling in reverse supply chain, and provides a decision reference for the remanufacturer. Moreover, this study defines the relationship between online platforms and the remanufacturer as the coexistence of delegation and cooperation. That is to say, the profit of recycling platforms will be more inseparable from the remanufacturer, and this model will be more helpful to incentivize online platforms to invest more recycling efforts to achieve win–win results. Furthermore, this study discusses profits and stability influenced by parameters fluctuation in a multi-period game.

Figure 2. The basic model.

Table 2. Parameters in the basic model.

Parameter	Definition
a	Potential demand of e-waste recycling market
b	Price elasticity coefficient of consumer participation in recycling
q_1	The amount obtained by the remanufacturer from the individual recycler
v	The remanufacturer's revenue from remanufacturing a unit of waste
π_1	Profit of the individual recycler
π_2	Profit of the remanufacturer
p_1	The recovery price of individual recyclers
w	The e-waste price obtained by remanufacturers through individual recyclers

3. The basic model

This section shows the basic model of e-waste recycling in Figure 2. Recyclers act as intermediaries between remanufacturers and consumers, gaining profit mainly by reselling recycled waste to remanufacturers. The remanufacturer is the end of the reverse supply chain, and plays the role of bridging the forward and reverse supply chains through the remanufacturing and secondary sales of used electronics.

To better illustrate the problem, this study merges the e-waste processing with the remanufacturing. Remanufacturers and individual recyclers are risk-neutral. The compilation of parameters and variable definitions is presented in Table 2.

It is possible to think of the process of recycling e-waste as one of meeting customer demand for recycling services, and market demand is influenced by things like recycling costs and consumer channel preferences. Individual recyclers obtain e-waste from consumers at price p_1, and remanufacturers obtain e-waste from individual recyclers at price w. Simplifying the model, assume that the marginal costs of the recycling platform and the remanufacturer are all internalized as sharing incentives and remanufacturing benefits, and set the marginal operating costs of both to zero. The profits of individual recycler and remanufacturer are as follows.

$$\pi_1 = (w - p_1)q_1$$
$$\pi_2 = (v - w)q_1.$$

Given the equation $q = a + bp$, the demand in the recycling market is directly proportional to the price paid for recycling. The corresponding equations are as follows.

$$\pi_1 = (w - p_1)(a + bp_1) = wa - p_1 a + bp_1 w - bp_1^2$$
$$\pi_2 = (v - w)q_1 = (v - w)(a + bp_1) = av - aw + bp_1 v - bp_1 w.$$

In this reverse supply chain, the remanufacturer occupies the position of leadership. The individual recycler, acting as a follower, decides on the recycling price p_1 based on the w decided by the remanufacturer before. The solution procedure is shown in Appendix A.1 and the results are as follows.

$$w^* = \frac{-a + bv}{2b}; p_1^* = \frac{-3a + bv}{4b}; \pi_1^* = (w^* - p_1^*)(a + bp_1^*) = \frac{(bv + a)^2}{16b}; \pi_2^* = (v - w^*)(a + bp_1^*) = \frac{(bv + a)^2}{8b}.$$

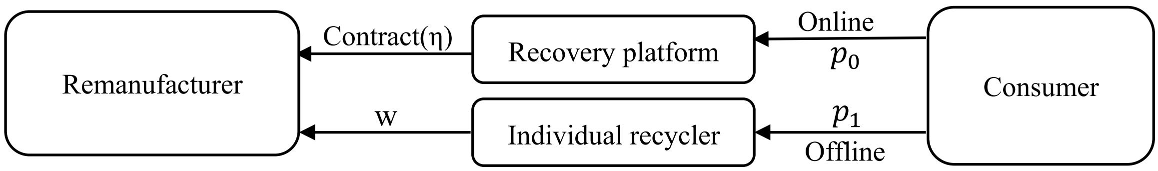

FIGURE 3. The single-platform model.

TABLE 3. Additional parameters in the single-platform model.

Parameter	Paraphrase
γ	Cross-sensitivity of online and offline recycling channel prices
q_0	The amount obtained by the remanufacturer from the recovery platform
q_1	The amount obtained by the remanufacturer from the individual recycler
ρ	Consumer preference of recycling platform (The diversion ratio of online channel to offline channel market size)
$1-\rho$	Consumer preference coefficient of individual recycler
π_0	Profit of the recovery platform
η	The profit allocation proportion from the remanufacturer to the platform
p_0	The recovery price of the recycle platform

When $w = w^*$ and $p_1 = p_1^*$, the profits of individual recyclers and remanufacturers will take maximum values, respectively π_1^* and π_2^*.

4. The single-platform model

This section considers a dual-channel reverse supply chain consisting of a remanufacturer, a recycling platform, and an individual recycler, as shown in Figure 3.

The model consists of two recycling channels: the recycling platform and the individual recycler. In this reverse supply chain, consumers make different decisions when choosing the recycling channel. Recycling platforms are intermediate transshipment channels, and their profit comes from revenue sharing of the remanufacturers. The additional parameters compared to the base model are in Table 3.

We assumed the remanufacturer must first come to an agreement with the recycling platform regarding the amount to be paid for the product's recycling in the platform channel, and the platform recycling price is lower than the price of waste purchased by remanufacturers from individual recyclers, otherwise individual recyclers will forward the e-waste to the recycling platform channel for higher returns. The inventory element has been left out of this model since it is anticipated that all recycled e-waste may be fully transshipped and disposed of. Based on prior studies [53], the following link exists between the amount of recycling and the price paid for recycling $(b > \gamma > 0)$.

$$q_0 = \rho a + bp_0 - \gamma p_1 \tag{1}$$

$$q_1 = (1-\rho)a + bp_1 - \gamma p_0. \tag{2}$$

Remanufacturers who recycle their products by platforms will give a share (η) of its profits to the platform. According to relevant research [35], the expansion of online platforms will result in an increase in market size, which will generate the "synergistic impacts" on upstream businesses that are connected to the recycling initiative of platforms, which will produce an advertising effect for the recycling platform with a value of $\eta p_0 q_0$.

The profit functions of recycling platforms (π_0), individual recyclers (π_1), and remanufacturers (π_2) are given below ($v > w, w > p_1, w > p_0$).

$$\pi_0 = (v - p_0)q_0\eta = \eta(v - p_0)(\rho a + bp_0 - \gamma p_1) \tag{3}$$

$$\pi_1 = (w - p_1)q_1 = (w - p_1)((1 - \rho)a + bp_1 - \gamma p_0) \tag{4}$$

$$\begin{aligned}\pi_2 &= (v - w)q_1 + v(1 - \eta)q_0 - p_0q_0 + \eta p_0q_0 \\ &= (v - w)((1 - \rho)a + bp_1 - \gamma p_0) + v(1 - \eta)(\rho a + bp_0 - \gamma p_1) - p_0(\rho a + bp_0 - \gamma p_1).\end{aligned} \tag{5}$$

4.1. Profit analysis of the remanufacturer in a single-platform model

This section explores the decision of the remanufacturer after it has developed an online recycling channel in light of the formula (3)–(5). In order to simplify the calculation without changing the results, b equals 1. The profit functions of recycling platforms, individual recyclers, and remanufacturers are as follows.

$$\begin{aligned}\pi_0 &= (v - p_0)q_0\eta = \eta v p_0 - \rho a\eta p_0 - \eta p_0p_0 - \eta v\gamma p_1 + \gamma\eta p_0p_1 + \rho a\eta v \\ &= p_0(\eta v - \rho a\eta) - \eta p_0^2 + \gamma\eta p_0p_1 - \eta v\gamma p_1 + \rho a\eta v\end{aligned} \tag{6}$$

$$\begin{aligned}\pi_1 &= (w - p_1)q_1 = (w - p_1)((1 - \rho)a + p_1 - \gamma p_0) \\ &= (1 - \rho)aw + wp_1 - w\gamma p_0 - (1 - \rho)ap_1 - p_1^2 + \gamma p_0p_1\end{aligned} \tag{7}$$

$$\begin{aligned}\pi_2 &= (v - w)q_1 + v(1 - \eta)q_0 - p_0q_0 \\ &= (v - w)((1 - \rho)a + p_1 - \gamma p_0) + v(1 - \eta)(\rho a + p_0 - \gamma p_1) - p_0(\rho a + p_0 - \gamma p_1).\end{aligned} \tag{8}$$

The remanufacturer plays a leading role in this reverse supply chain, first deciding on the w and η. After that, the recycling platform and the individual recycler act as followers, defining recycling prices like p_0 and p_1. Appendix A.2 depicts the solution procedure. The findings demonstrate that the Hesse matrix of the remanufacturer's profit with w and η is indeterminate. It is challenging to directly analysis profits trend of the remanufacturer as parameters change. Therefore, we'll employ it by numerical simulation.

Based on our research into the actual lithium battery recycling market, as well as the secondary utilization value conferred by the process of echelon utilization, disassembly, separation, and utilization of lithium batteries after recycling, we determined that the average recycling price of discarded lithium batteries is between 6 and 10 yuan/kg (the parameter values of subsequent research refer to this range). Referring to the reality, we assign the parameters as follows: $v = 6$, $\rho = 0.6$, $a = 1.1$, $\gamma = 0.4$, $b = 0.5$, into expressions of (8), the profit of the remanufacturer can be shown in Figure 4 (The valid part is "$\pi_2 > 0$").

It's shown that from Figure 4a, in the single-platform recycling structure, the remanufacturer's profit decreases as the proportion(η) of recycling platform sharing increases. When combined with the analysis in Figure 4c, this downward trend becomes more pronounced as w increases in value. As shown in Figure 4b, if the remanufacturer's profits are to remain constant, the remanufacturer must raise the recycling total price from the individual recycler to compensate for this loss when the remanufacturer's profit allocation proportion to the recycling platform rises. As shown in Figures 4a and 4d, it can be seen that the remanufacturer's profit rises as w grows, but this upward tendency declines as η increases. Increases in η may enhance revenue for remanufacturers on the one hand, but may reduce profits due to excessive revenue sharing given to recycling platforms, depending on the operational conditions. It is widely understood that when remanufacturers can earn a sizable profit from the platform for recycling, their operating pressure will decrease and their requirement for another channel will decrease, meaning that remanufacturers will alienate some more profits to recyclers.

4.2. Dynamical systems analysis

With the development of the web, the share of online recycling channels is expanding, and many remanufacturers will entrust online platforms to participate in recycling, generating channel competition with traditional recyclers. Due to the complexity of reverse supply chain, it is difficult for enterprises to make accurate judgment

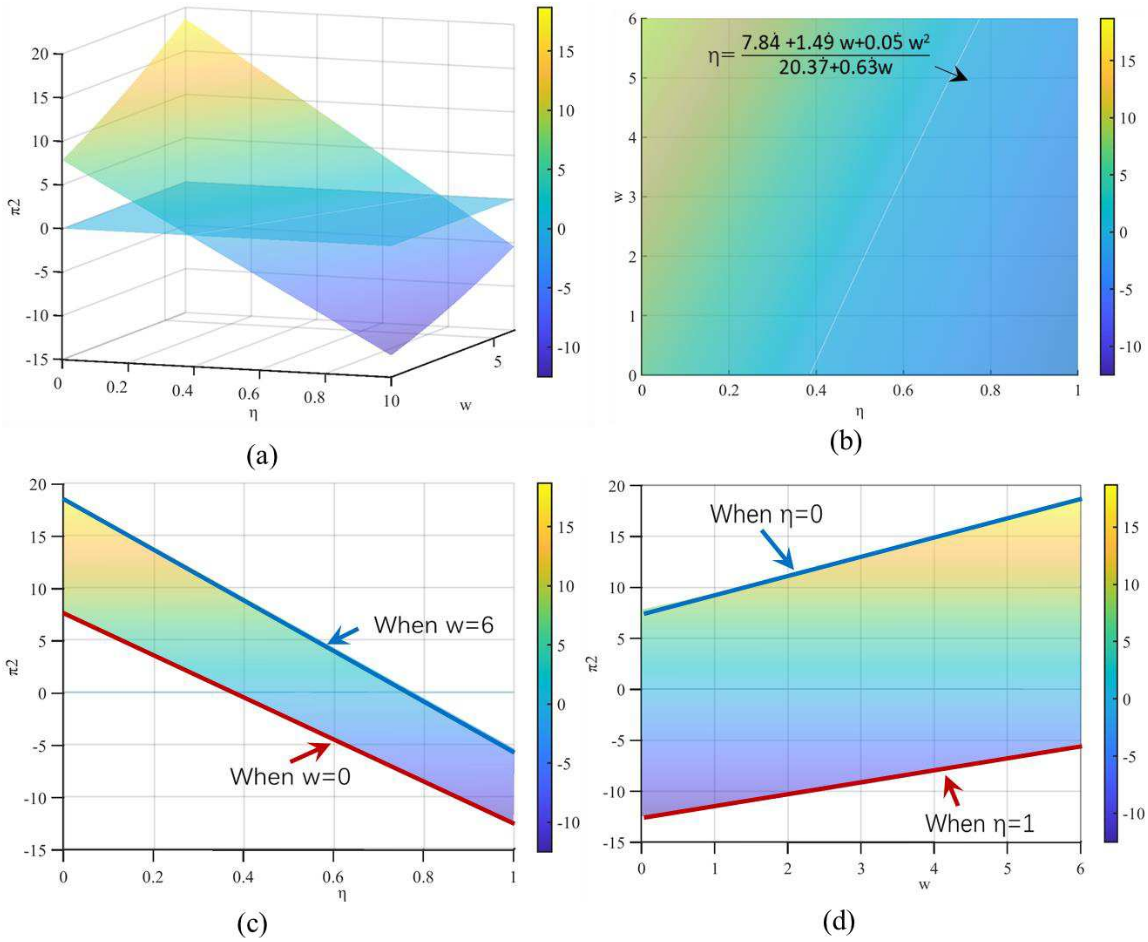

FIGURE 4. The relationship of "$\pi_2 - \eta - w$" in the single platform model. (a) The 3D view of "$\pi_2 - \eta - w$". (b) The line of "$\eta - w$" when $\pi_2 = 0$. (c) π_2 when $w = 0\&6$, and $0 \leq \eta \leq 1$. (d) π_2 when $\eta = 0\&1$, and $0 \leq w \leq 6$.

on the market based on limited information. As a result, only based on the current operational data can enterprises make relevant decisions in the next stage. When the current marginal benefit is positive, the company will continue to advance in the current direction, and *vice versa*, adjust the operation direction. The study of complexity focuses not only on "stable states", but also on "how states tend to be stable". The first partial derivative of formula (3)–(5) can be obtained as follows:

$$\begin{cases} \frac{\partial \pi_0}{\partial p_0} = \eta(b_0 v - \rho a + \gamma p_1) - 2b\eta p_0 \\ \frac{\partial \pi_1}{\partial p_1} = w b_1 - (1-\rho)a + \gamma p_0 - 2bp_1 \\ \frac{\partial \pi_2}{\partial w} = -(1-\rho)a - bp_1 + \gamma p_0. \end{cases} \tag{9}$$

The setting $g_i > 0 (i = 0, 1, 2, 3)$, accordingly, in this study reflects the rate of change in decision-making in each firm. In complicated systems, participants in the recycling supply chain make decisions based on finite rational expectations. The dynamic decision-making process of this recycling system is expressed as follows.

$$\begin{cases} p_{0,t+1} = p_{0,t} + g_0 p_{0,t} \frac{\partial \pi_0(t)}{\partial p_0(t)} \\ p_{1,t+1} = p_{1,t} + g_1 p_{1,t} \frac{\partial \pi_1(t)}{\partial p_1(t)} \\ w_{t+1} = w_t + g_2 w_t \frac{\partial \pi_2(t)}{\partial w(t)}. \end{cases} \tag{10}$$

Then we get the following formula:

$$\begin{cases} p_{0,t+1} = p_{0,t} + g_0 p_{0,t}(\eta(bv - \rho a + \gamma p_1) - 2b\eta p_0) \\ p_{1,t+1} = p_{1,t} + g_1 p_{1,t}(w_t b - (1-\rho)a + \gamma p_0 - 2bp_1) \\ w_{t+1} = w_t + g_2 w_t(-(1-\rho)a - bp_1 + \gamma p_0). \end{cases} \tag{11}$$

After multiple rounds of games, the supply chain system (11) becomes stable when $p_{i,t+1} = p_{i,t}$ and $w_{t+1} = w_t$. In equilibrium, all participants cannot increase their profits by changing their decisions. As a result, in the stable state, each participant can maximize the profit. Critical Points are as follows.

$$E_1 = (0,0,0);\quad E_2 = \left(\frac{bv - a\rho}{2b}, 0, 0\right);\quad E_3 = \left(0, \frac{a - a\rho}{2b}, 0\right);\quad E_4 = \left(0, \frac{-a + a\rho}{b}, \frac{-a + a\rho}{b}\right);$$
$$E_5 = \left(\frac{-\gamma a - ab\rho + 2b^2 v + a\rho\gamma}{4b^2 - \gamma^2}, \frac{-2ab + 2ab\rho - a\rho\gamma + b\gamma v}{4b^2 - \gamma^2}, 0\right);$$
$$E_6^* = \left(\frac{-\gamma a - ab\rho + b^2 v + a\rho\gamma}{2b^2 - \gamma^2}, \frac{-2ab + 2ab\rho - a\rho\gamma + b\gamma v}{2b^2 - \gamma^2}, \frac{-2ab + 2ab\rho - a\rho\gamma + b\gamma v}{2b^2 - \gamma^2}\right).$$

When $E_6^* > 0$, the completely nonzero stable point exists. In addition, as is tested in Appendix A.4 by solving the Jacobi matrix of each stable point, the conditions for the stability of E_6^* are as follows:

$$\begin{cases} -(\varphi_1 + \varphi_2 + \varphi_3) > 0 \\ \varphi_1\varphi_2 + \varphi_1\varphi_3 + \varphi_2\varphi_3 - \eta g_0 g_1 p_0 p_1 \gamma^2 + wb^2 g_1 g_2 p_1 > 0 \\ -\varphi_1\varphi_2\varphi_3 - \eta\gamma^2 wbg_0 g_1 g_2 p_0 p_1 + \eta\gamma^2 g_0 g_1 p_0 p_1 \varphi_3 - wg_1 g_2 p_1 b^2 \varphi_1 > 0 \end{cases}$$
$$\varphi_1 = 1 + \frac{4\gamma abg_0\eta(1-\rho) + 2ab^2 g_0\eta\rho - 2b^3 vg_0\eta}{2b^2 - \gamma^2};\quad \varphi_2 = 1 + g_1\left(\frac{4ab^2 - 4ab^2\rho + 2ba\rho\gamma - 2b^2\gamma v}{2b^2 - \gamma^2}\right);$$
$$\varphi_3 = 1. \tag{12}$$

When the recycling platform, individual recycler and the remanufacturer adjust their decisions at speeds of $g_0/g_1/g_2$ that are limited within the formula (12), E_6 is locally stable. According to (12), we can conclude the Proposition 1.

$$g_0 \in \left\{ \begin{array}{l} g_0 \Big| \Big\{ g_0 < -\frac{3C + g_1 D}{A+B},\ \text{when } A+B > 0 \Big\} \cap \Big\{ g_0 > -\frac{3C + g_1 D}{A+B},\ \text{when } A+B < 0 \Big\} \\ \cap \Big\{ g_0 > -\frac{2g_1 CD + wb^2 g_1 g_2 p_1 C^2 + 3C^2}{D(A+B)g_1 + 2C(A+B) - \eta g_1 p_0 p_1 \gamma^2 C^2},\ \text{when } D(A+B)g_1 + 2C(A+B) - \eta g_1 p_0 p_1 \gamma^2 C^2 > 0 \Big\} \\ \cap \Big\{ g_0 < -\frac{2g_1 CD + wb^2 g_1 g_2 p_1 C^2 + 3C^2}{D(A+B)g_1 + 2C(A+B) - \eta g_1 p_0 p_1 \gamma^2 C^2},\ \text{when } D(A+B)g_1 + 2C(A+B) - \eta g_1 p_0 p_1 \gamma^2 C^2 < 0 \Big\} \\ \cap \Big\{ g_0 < -\frac{Cwg_1 g_2 p_1 b^2 + C + g_1 D}{g_1 D(A+B)},\ \text{when } g_1 D(-A-B) < 0 \Big\} \\ \cap \Big\{ g_0 > -\frac{Cwg_1 g_2 p_1 b^2 + C + g_1 D}{g_1 D(A+B)},\ \text{when } g_1 D(-A-B) > 0 \Big\} \end{array} \right\}$$
$$A = 4\gamma ab\eta(1-\rho); B = 2ab^2\eta\rho - 2b^3 v\eta; C = 2b^2 - \gamma^2; D = 4ab^2 - 4ab^2\rho + 2ba\rho\gamma - 2b^2\gamma v \tag{13}$$

$$g_1 \in \left\{ \begin{array}{l} g_1 \middle| \left\{ g_1 < -\frac{3C+g_0(A+B)}{D},\ \text{when } D>0 \right\} \cap \left\{ g_1 > -\frac{3C00+g_0(A+B)}{D},\ \text{when } D<0 \right\} \\ \cap \left\{ g_1 > -\frac{2g_0C(A+B)+3C^2}{D(A+B)g_0+2CD+wb^2g_2p_1C^2-\eta g_0p_0p_1\gamma^2C^2}, \right. \\ \left. \text{when } D(A+B)g_0+2CD+wb^2g_2p_1C^2-\eta g_0p_0p_1\gamma^2C^2>0 \right\} \\ \cap \left\{ g_1 < -\frac{2g_0C(A+B)+3C^2}{D(A+B)g_0+2CD+wb^2g_2p_1C^2-\eta g_0p_0p_1\gamma^2C^2}, \right. \\ \left. \text{when } D(A+B)g_0+2CD+wb^2g_2p_1C^2-\eta g_0p_0p_1\gamma^2C^2<0 \right\} \\ \cap \left\{ g_1 < \frac{-C}{g_0D(A+B)+Cwg_2p_1b^2+D},\ \text{when } g_0D(A+B)+Cwg_2p_1b^2+D>0 \right\} \\ \cap \{ g_1 > \frac{-C}{g_0D(A+B)+Cwg_2p_1b^2+D},\ \text{when } g_0D(A+B)+Cwg_2p_1b^2+D<0 \} \end{array} \right\} \tag{14}$$

$$g_2 \in \left\{ \begin{array}{l} g_2 \middle| \left\{ g_2 > \frac{g_0(-D(A+B)g_1-2C(A+B)+\eta g_1p_0p_1\gamma^2C^2)-2g_1CD-3C^2}{wb^2g_1p_1C^2},\ \text{when } wb^2g_1p_1C^2>0 \right\} \\ \cap \left\{ g_2 < \frac{g_0(-D(A+B)g_1-2C(A+B)+\eta g_1p_0p_1\gamma^2C^2)-2g_1CD-3C^2}{wb^2g_1p_1C^2},\ \text{when } wb^2g_1p_1C^2<0 \right\} \\ \cap \left\{ g_2 > \frac{g_0g_1D(-A-B)-C-g_1D}{wg_1g_2p_1b^2},\ \text{when } wg_1g_2p_1b^2<0 \right\} \\ \cap g_2 < \frac{g_0g_1D(-A-B)-C-g_1D}{wg_1g_2p_1b^2},\ \text{when } wg_1g_2p_1b^2>0 \end{array} \right\}. \tag{15}$$

Proposition 1. *The price adjustment speed of enterprise (g_0 of recycling platforms, g_1 of individual recyclers, g_2 of remanufacturers) within the appropriate range can effectively maintain the market stable. In this reverse supply chain, when $g_0 \in$ (13)/ $g_1 \in$ (14)/$g_2 \in$ (15), the system can remain stable. At this time, the equilibrium point is ${E_6}^*$. If the speed of price adjustment exceeds the critical range, the system will appear the phenomenon of chaos or bifurcation.*

4.3. Parameters analysis

4.3.1. The proportion of profit allocating to the platform

We analyze how the profit of the remanufacturer is affected by the proportion allocated to the recycling platform. Substitute the stable price into the derivative of $\pi_2(b > \gamma > 0 \rightarrow 2b^2 - \gamma^2 > 0)$:

$$\frac{\partial \pi_2}{\partial \eta} = -v(\rho a + bp_0 - \gamma p_1) = \frac{-ab^2\rho v + ab\gamma v(1-\rho) + bv^2\left(b^2-\gamma^2\right)}{2b^2-\gamma^2}. \tag{16}$$

As shown in (17), the threshold value ρ^* is $\frac{ab\gamma v+bv^2\left(b^2-\gamma^2\right)}{bv(b-\gamma)}$.

$$\begin{cases} \rho < \frac{ab\gamma v+bv^2\left(b^2-\gamma^2\right)}{abv(b-\gamma)},\ \text{when } \ -ab^2\rho v + ab\gamma v(1-\rho) + bv^2\left(b^2-\gamma^2\right) > 0 \\ \rho > \frac{ab\gamma v+bv^2\left(b^2-\gamma^2\right)}{abv(b-\gamma)},\ \text{when } \ -ab^2\rho v + ab\gamma v(1-\rho) + bv^2\left(b^2-\gamma^2\right) < 0. \end{cases} \tag{17}$$

Proposition 2. *As people increasingly recognize online channels, the effect of the proportion (η) allocated to the recycling platform on the profit of the remanufacturer (π_2) will turn from positive to negative. When people's acceptance (ρ) of the online channel is low, the allocation proportion (η) is positively associated with the profit of the remanufacturer (π_2). The threshold value for people's acceptance (ρ) of online channels is $\rho^* = \frac{ab\gamma v+bv^2\left(b^2-\gamma^2\right)}{bv(b-\gamma)}$.*

4.3.2. The impact of the consumer recycling preference

(1) The impact on profits
This section analyzes the impact of the consumers' recognition of online platforms ρ on the profits of recycling platforms, individual recyclers, and remanufacturers.

① The recycling platform

$$\begin{aligned}\pi_0 &= (v-p_0)q_0\eta = \eta v b p_0 - \rho a \eta p_0 - b\eta p_0 p_0 - \eta v \gamma p_1 + \gamma \eta p_0 p_1 + \rho a \eta v\\ &= p_0(\eta v b - \rho a \eta) - b\eta p_0^2 + \gamma\eta p_0 p_1 - \eta v\gamma p_1 + \rho a \eta v\\ \frac{\partial \pi_0}{\partial \rho} &= a\eta(v-p_0) > 0. \end{aligned} \tag{18}$$

According to (18) and the reality, the increased consumers' recognition of online platforms will drive them to recycle e-waste online. This process will bring more money to the online channel. And as the share ratio η grows, the recycling platform's profit grows even more. Then we can conclude the Proposition 3.

Proposition 3. *As consumers become more aware of the online channel, the profit of recycling platforms will rise, and this rising trend will be compounded by an increase in the proportion of remanufacturer's profit allocation to the platform.*

② The individual recycler

$$\begin{aligned}\pi_1 &= (w-p_1)q_1 = (w-p_1)((1-\rho)a + bp_1 - \gamma p_0)\\ \frac{\partial \pi_1}{\partial \rho} &= a(p_1 - w) < 0. \end{aligned} \tag{19}$$

The profit of the individual recycler will decline as consumers become more aware of the online channel, and the larger the recycling market capacity, the faster the decline will happen. When people gradually recognize online recycling channels, offline channels will lose some customers, and more and more people will choose online recycling, reducing the market share of offline channels and causing a decline in profits.

Proposition 4. *The online recycling will compete with the individual recycling as online recycling acceptance of consumers grows. As a result, the profit of the individual recycler will tend to decay. The larger the recycling market capacity, the more pronounced this trend will be.*

③ The remanufacturer

$$\begin{aligned}\pi_2 &= (v-w)q_1 + v(1-\eta)q_0 - p_0 q_0\\ &= (v-w)((1-\rho)a + bp_1 - \gamma p_0) + v(1-\eta)(\rho a + bp_0 - \gamma p_1) - p_0(\rho a + bp_0 - \gamma p_1)\\ \frac{\partial \pi_2}{\partial \rho} &= (w - v\eta - p_0)a. \end{aligned} \tag{20}$$

Since "$w > p_1, w > p_0, p_0 < p_1$", the symbol (positive or negative) of (20) cannot be directly determined. When $w - v\eta - p_0 > 0$, namely $\frac{w-p_0}{v} > \eta$, $\frac{\partial \pi_2}{\partial \rho} > 0$, the proportion ($\eta$) of profit allocation to the platform is low, and the profit of the remanufacturer are increasing as online recycling acceptance of consumers grows. But this is not always the case, when $\frac{w-p_0}{v} < \eta$, that is, when the remanufacturer allocates a large proportion of its profit to the recycling platform, $\frac{\partial \pi_2}{\partial \rho} < 0$, the profit of the remanufacturer is on a downward trend.

Proposition 5. *The impact of online recycling acceptance of consumers on the profit of the remanufacturer tends to increase and then decline as the proportion (η) of profit allocation to the platform increases. When remanufacturers allocate a small percentage of profits to recycling platforms, their profits increase as online channels become more widely accepted. Conversely, when remanufacturers allocate a larger percentage of profits to recycling platforms, their profits decrease as online channels become more widely accepted. The critical value is* $\eta^* = \frac{w-p_0}{v}$.

(2) The impact on the stability

We studied the impact of online recycling acceptance of consumers on the price stability E_6^*. The recycling prices are:

$$P_0^* = \frac{-\gamma a - ab\rho + b^2 v + a\rho\gamma}{2b^2 - \gamma^2} = \frac{1}{2b^2 - \gamma^2}\left(a\rho(\gamma - b) - \gamma a + b^2 v\right);$$
$$P_1^* = \frac{-2ab + 2ab\rho - a\rho\gamma + b\gamma v}{2b^2 - \gamma^2} = \frac{1}{2b^2 - \gamma^2}(a\rho(2b - \gamma) - 2ab + b\gamma v);$$
$$W^* = \frac{-2ab + 2ab\rho - a\rho\gamma + b\gamma v}{2b^2 - \gamma^2} = \frac{1}{2b^2 - \gamma^2}(a\rho(2b - \gamma) - 2ab + b\gamma v).$$

Considering $b > \gamma$, $\gamma - b < 0$, we can know:

$$\frac{\partial P_0^*}{\partial \rho} = \frac{a(\gamma - b)}{2b^2 - \gamma^2} < 0; \frac{\partial P_1^*}{\partial \rho} = \frac{a(2b - \gamma)}{2b^2 - \gamma^2} < 0; \frac{\partial W^*}{\partial \rho} = \frac{a(2b - \gamma)}{2b^2 - \gamma^2} > 0.$$

The following proposition is obtained.

Proposition 6. *As online recycling acceptance of consumers grows, the recycling price of the online platform will fall, the recycling price of the individual recycler will increase, and the remanufacturer will raise the price of purchasing e-waste from the individual recycler.*

4.3.3. Numerical analysis

Due to the profit of the remanufacturer is affected by both the online recycling acceptance (ρ) of consumers and the proportion (η) of profit allocation to the platform, it is difficult to visually describe their relationship and the effect on the remanufacture by formula analysis. The numerical simulation method is used to express the trend more intuitively. As a result, we will examine how these two variables impact the profit of the remanufacturer by numerical analysis. Based on the analysis and standardization of the average recycling price of 25-inch TV in Shanghai and the average processing cost of such products in the waste electronic products recycling enterprises disclosed in "China Waste Recycling Network (www.zgfeipin.cn)", the values of the parameters in the numerical simulation are determined. Referring to the reality, we assign the parameters of π_2 as follows: $v = 6$, $w = 4$, $p_0 = 3$, $p_1 = 6$, $a = 1.1$, $\gamma = 0.4$, $b = 0.5$.

(1) Examine the influence of η and ρ(rho) on π_2.

The graph makes it clear that influences of parameters on the profit of the remanufacturer are dynamic and interdependent. As a result, when the remanufacturer expands their online recycling channel, they must consider the current business environment and make prudent contract parameter choices. Interestingly, our findings differ from what is commonly assumed to be true. For the remanufacture, the online recycling acceptance (ρ) of consumers is not the higher the better and the proportion (η) of profit allocation to the platform is not the lower the better, which must be balanced comprehensively.

As shown in Figure 6, there is always a line at the highest point of all "$\rho - \eta$" combinations, and all points of this curve allow the remanufacturer to obtain a relatively high profit. This line is formed by the meeting of two faces. One of them is the surface as shown in Figure 5, and the other is a surface perpendicular to the coordinate plane of "$\rho - \eta$", *i.e.*, the plane "$\rho + \eta - 1 = 0$", through the two points of $(0, 1, 4.56)$ and $(1, 0, 8.86)$.

Figure 6 shows that, under various decision combinations, the remanufacturer's highest profit point is distributed on the curve "$\rho + \eta - 1 = 0$" in the profit function. The intersection line between the two surface, as shown in Figure 7.

When the decision-points are dispersed on the curve in Figure 7, the better profits for the remanufacturer are obtained.

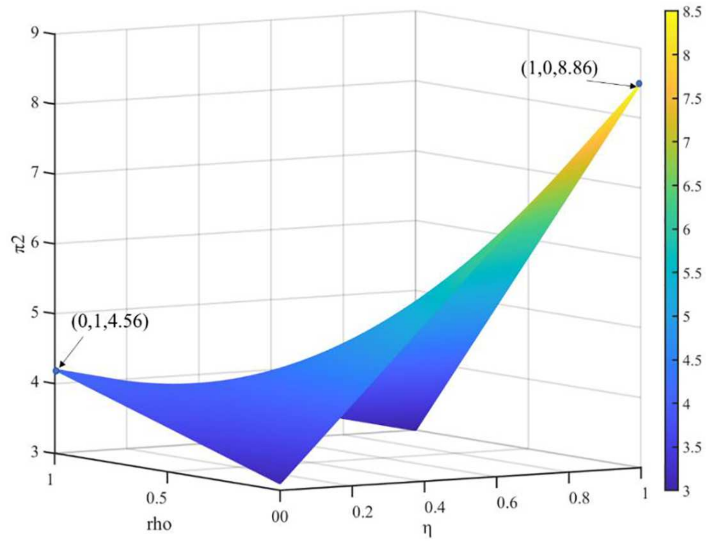

FIGURE 5. Interaction effect of ρ, η on the profit of the remanufacturer.

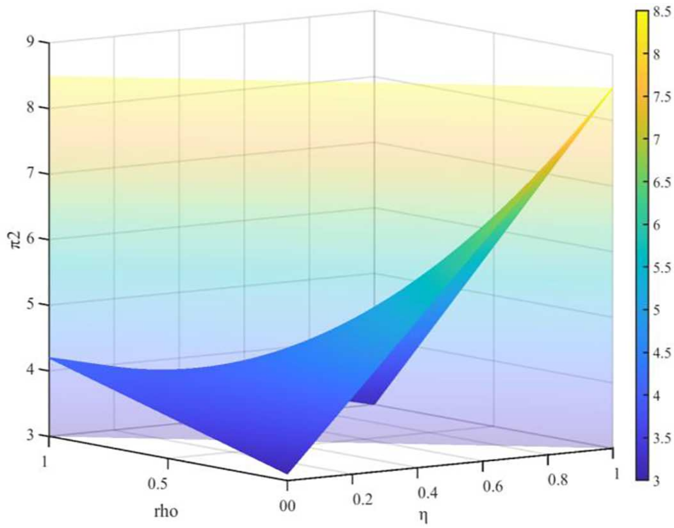

FIGURE 6. The value combination curve with the highest profit.

(2) Given two scenarios of the allocation proportion (η) at 0.9 and 0.1, the impact of consumer recognition (ρ) on remanufacturer profits is discussed, as illustrated in Figure 8.
This result is just right to validate the Proposition 5. When η takes different values, the impact of the online recycling acceptance (ρ) of consumers on the profit of the remanufacturer will follow different patterns. When η is small, there is a positive correlation. Inversely, there is an inverse correlation.
(3) Given two scenarios of the online recycling acceptance (ρ) of online channels at 0.9 and 0.1, the impact of the allocation proportion (η) on the profit of the remanufacturer is discussed in Fig. 9.

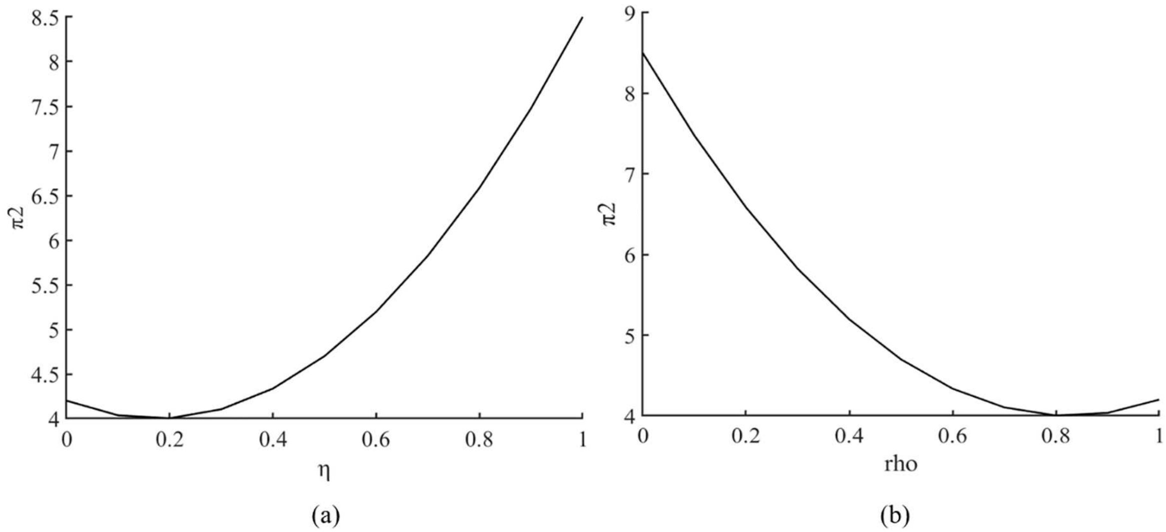

FIGURE 7. The optimal profit combination of the remanufacturer (when $\rho + \eta = 1$).

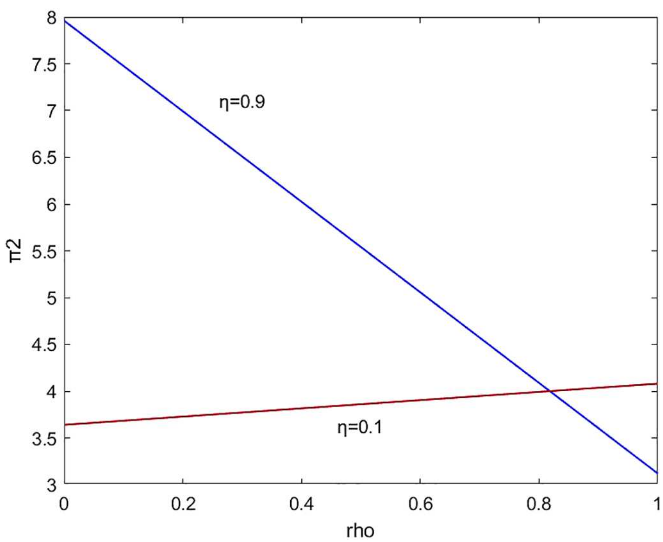

FIGURE 8. The effect of ρ on the profit of the remanufacturer at different η.

Contrary to reality, the findings indicate that when consumers don't accept recycling online, remanufacturers are more likely to expand their channels into recycling platforms, which results in higher profits for them. In contrast, when consumers are highly appreciating online channels, remanufacturers are less likely to expand their channels into recycling platforms, which results in lower profits for remanufacturers. This is in line with the Proposition 2.

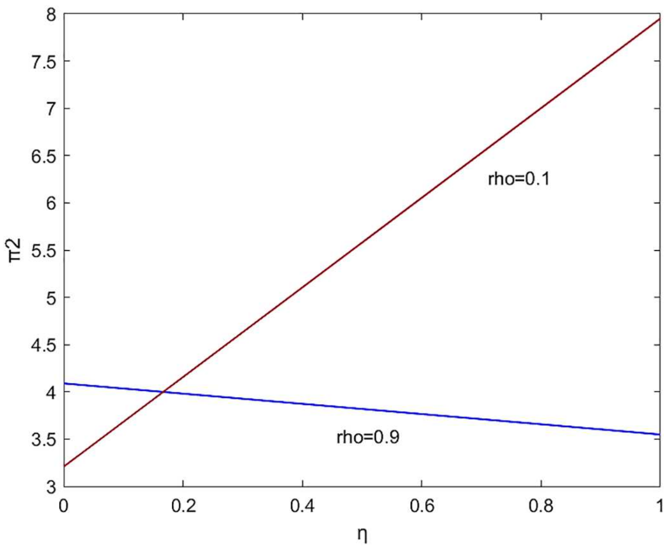

FIGURE 9. The effect of η on the profit of the remanufacturer at different ρ.

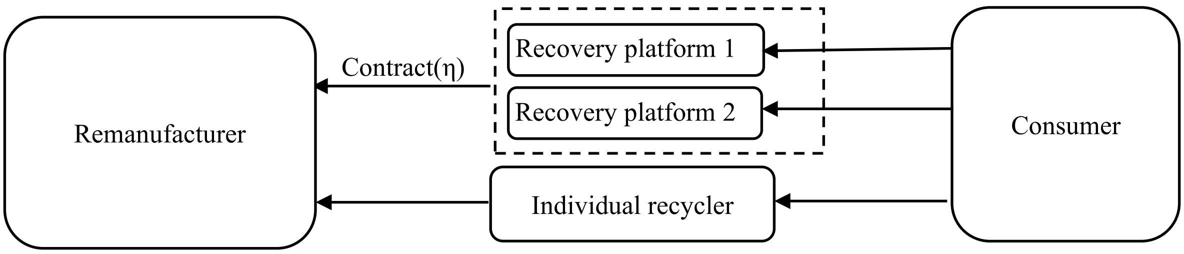

FIGURE 10. Dual-platform recycling structure diagram.

5. THE DUAL-PLATFORM MODEL

The rationality of enterprises often pushes them to allocate scarce resources to the business structure with high rates of return. When a remanufacturer recycles online *via* one single platform, the centralization of its resources is advantageous for the growth of this platform, but it also results in "putting all the eggs in one basket", and the fluctuations of this platform will leave greater risks. In order to spread risks, remanufacturers occasionally tend to expand more than one recycling platform to reduce risk. Whether recycling through two platforms is superior to single-platform recycling for remanufacturers warrants further investigation. There is a reverse supply chain structure including two platforms for recycling and one individual recycler, as well as one remanufacturer of electronic products in Figure 10.

Two recycling platforms and independent recyclers compete with one another in this reverse supply chain. Consumers can choose recycling channels according to their preferences. The additional symbols of the dual-platform model are shown Table 4.

Based on the price elasticity theory, the demand model established on linear function can better express the influence of different recovery prices under different recycling channels. The recycling demand of platform1, platform2, and the individual recycler are provided as follows ($b > \gamma_1, \gamma_2, \gamma_3 > 0$).

$$q_{01} = \rho\lambda a + bp_{01} - \gamma_3 p_{02} - \gamma_1 p_1$$

TABLE 4. Parameters for dual-platform models.

Parameter	Paraphrase
γ_1	Cross-sensitivity of prices in the online channel 1 and the offline channel
γ_2	Cross-sensitivity of prices in the online channel 2 and the offline channel
γ_3	Cross-sensitivity of prices in the online channel 1 and the online channel 2
λ	Share of platform 1 in the e-recycling market
$1-\lambda$	Share of platform 2 in the e-recycling market
q_{01}	The amount obtained by the remanufacturer from the recovery platform 1
q_{02}	The amount obtained by the remanufacturer from the recovery platform 2
π_{01}	Profit of the recovery platform 1
π_{02}	Profit of the recovery platform 2
p_{01}	The recovery price of platform 1
p_{02}	The recovery price of platform 2

$$q_{02} = \rho(1-\lambda)a + bp_{02} - \gamma_3 p_{01} - \gamma_2 p_1$$
$$q_1 = (1-\rho)a + bp_1 - \gamma_1 p_{01} - \gamma_2 p_{02}.$$

The total number of products obtained by the remanufacturer is the sum of the three recycling channels. The profit functions of platform1, platform2, individual recycler and remanufacturer are respectively:

$$\pi_{01} = (v-p_{01})q_{01}\eta = (v-p_{01})(\rho\lambda a + bp_{01} - \gamma_3 p_{02} - \gamma_1 p_1)\eta \tag{21}$$
$$\pi_{02} = (v-p_{02})q_{02}\eta = (v-p_{02})(\rho(1-\lambda)a + bp_{02} - \gamma_3 p_{01} - \gamma_2 p_1)\eta \tag{22}$$
$$\pi_1 = (w-p_1)q_1 = (w-p_1)[(1-\rho)a + bp_1 - \gamma_1 p_{01} - \gamma_2 p_{02}] \tag{23}$$
$$\pi_2 = (v-w)q_1 + v(1-\eta)(q_{01}+q_{02}) - (p_{01}q_{01} + p_{02}q_{02}) + \eta(p_{01}q_{01} + p_{02}q_{02}) \tag{24}$$
$$\begin{aligned}\pi_2 &= (v-w)q_1 + v(1-\eta)(q_{01}+q_{02}) - (p_{01}q_{01} + p_{02}q_{02}) + \eta(p_{01}q_{01} + p_{02}q_{02})\\ &= (v-w)((1-\rho)a + bp_1 - \gamma_1 p_{01} - \gamma_2 p_{02}) + v(1-\eta)\begin{pmatrix} \rho\lambda a + bp_{01} - \gamma_3 p_{02} - \gamma_1 p_1 \\ +\rho(1-\lambda)a + bp_{02} - \gamma_3 p_{01} - \gamma_2 p_1 \end{pmatrix}\\ &\quad + (\eta-1)(p_{01}(\rho\lambda a + bp_{01} - \gamma_3 p_{02} - \gamma_1 p_1) + p_{02}(\rho(1-\lambda)a + bp_{02} - \gamma_3 p_{01} - \gamma_2 p_1)).\end{aligned} \tag{25}$$

5.1. Profit analysis of the remanufacturer in the dual-platform model

As shown in Appendix A.3, in this reverse supply chain, the remanufacturer first determines w and η. After that, recycling platforms and the individual recycler, as followers, decide recycling prices of p_{01}, p_{02} and p_1 according to the η and w determined by the remanufacturer. Substituting p_{01}^*, p_{02}^* and p_1^* into the profit of the remanufacturer, the Hesse matrix of the profit function (π_2) about w and η is indefinite, which is difficult to be analyzed on the formula itself. Therefore, the numerical simulation is conducted to analyze the profit trend. Based on the reality, assigning parameters as follows: $v = 6$, $\rho = 0.6$, $a = 1.1$, $\gamma_1 = \gamma_2 = \gamma_3 = 0.4$, $b = 0.5$, $\lambda = 0.3$, the relationship of "$\pi_2 - \eta - w$" is shown in Figure 11.

Figure 11a shows that the profit of the remanufacturer positively associated with the profit allocation proportion η and negatively associated with the recycling price of the individual recycler. Figures 11a and 11b show that the parameters of η and w exhibit a curve-related relationship, and with the increase of w, η tend to increase rapidly at first and then increase slowly. Figures 11c and 11a show that the profit of the remanufacturer will decrease with the increase of η and this trend will be more pronounced as w increases. Figures 11d and 11a show that the profit of the remanufacturer is positively connected to w and this trend will be more pronounced as η decreases.

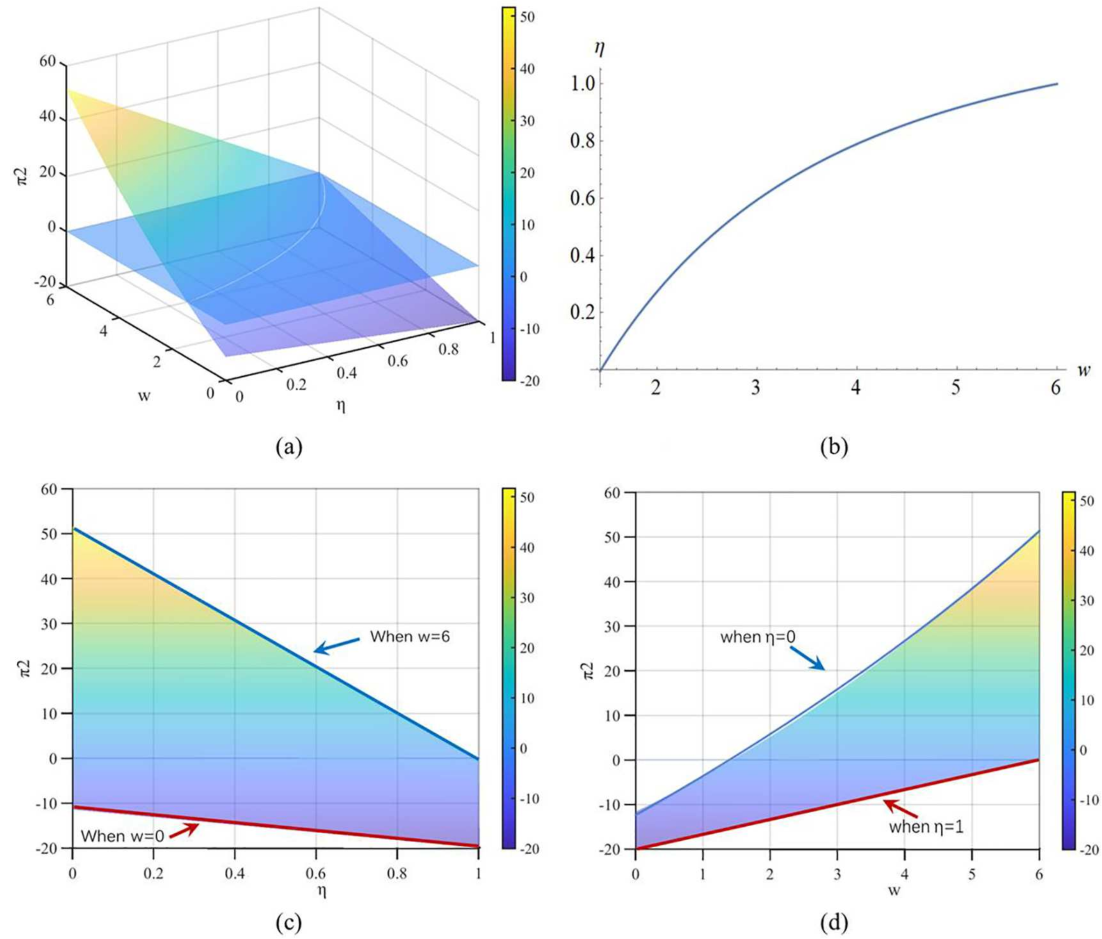

FIGURE 11. The relationship of "$\pi_2 - \eta - w$" under dual-platform model. (a) The relationship of "$\pi_2 - \eta - w$". (b) The line of "$\eta - w$" when $\pi_2 = 0$. (c) π_2 when $w = 0\&6$, and $0 \leq \eta \leq 1$. (d) π_2 when $\eta = 0\&1$, and $0 \leq w \leq 6$.

5.2. Parameter analysis

This section analyzes the relationship between profit allocation proportion η, the acceptation of online channel ρ and the profit the remanufacturer. Based on the reality, assigning the parameters as follows: $v = 6$, $w = 4$, $a = 1.1$, $\gamma_1 = \gamma_2 = \gamma_3 = 0.4$, $b = 0.5$, $\lambda = 0.3$, the relationship of "$\pi_2 - \eta - w$" is shown in Figure 12 ($0 < \rho, \eta < 1$; only the part that satisfied "$\pi_2 > 0$" is valid).

The profit of the remanufacturer is negatively related to the profit allocation proportion η and the consumer's preference coefficient ρ for online recycling channels, and the influence of η is much greater than ρ. It can be seen that when ρ takes a specific value, π_2 and η keep a simple linear correlation. According to the function of $\eta - \rho$, Figures 12b and 12c, we can analysis that when η takes a constant value, the influence of ρ on π_2 is not a simple linear correlation.

Regardless of the actual situation for the time being, from the mathematical point of view, when the coefficient ρ is limited to $-8 \leq \rho \leq 40$, as shown in Figure 13a, the relationship between π_2 and ρ presents a parabolic shape with an upward opening. Returning to the real problem, the part of $0 \leq \rho \leq 1$ is shown in Figure 13c.

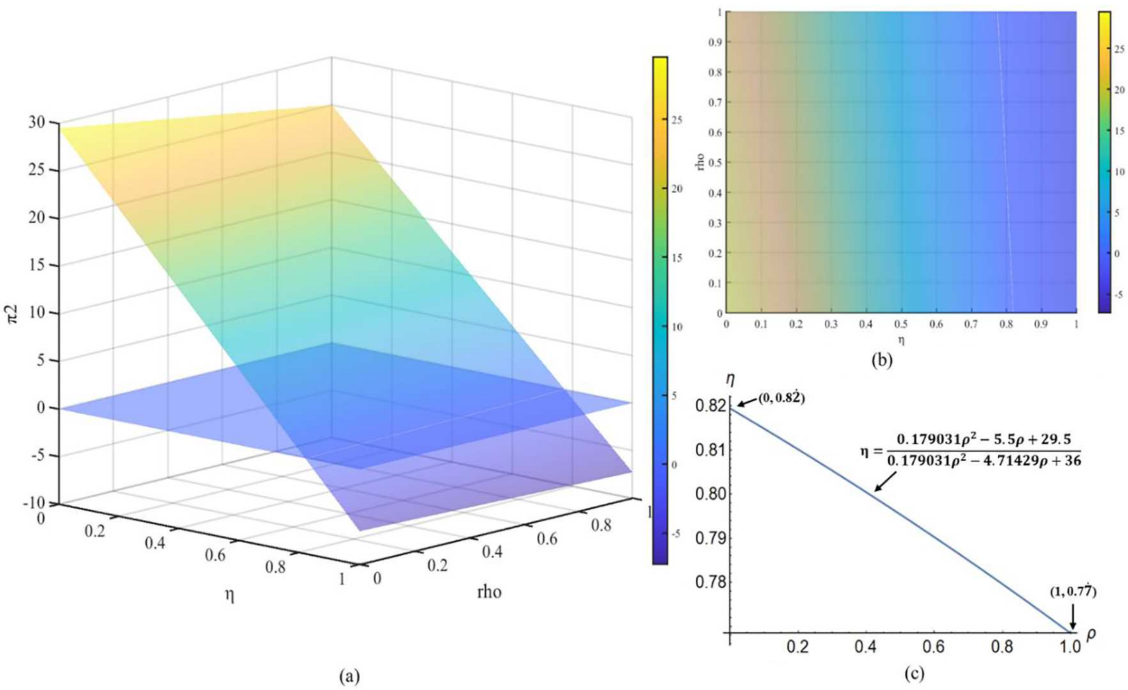

FIGURE 12. The relationship of "$\pi_2 - \eta - \rho$" under dual-platform structure. (a) The relationship of "$\pi_2 - \eta - \rho$ (rho)". (b) The view of "$\rho o \eta$" (the white line is intersection). (c) The intersection (when $\pi_2 = 0$).

By comparing Figures 13c and 13d, it can be concluded that with the increase of η, the decline trend of π_2 affected by ρ will slow down. According to the analysis in Figures 13a and 13b, the π_2 image, as a unilateral part of a concave paraboloid with an upward opening, is always higher on the side with $\rho = 0$ than on the side with $\rho = 1$ in the process of decreasing with the increase of η, and the descending speed of the former will be relatively faster.

6. Comparison

The remanufacturer changes their business pattern by developing online recycling platforms, but it is worth pondering whether this change will generate additional earnings. From the perspective of the remanufacturer, this study takes into account the fundamental context of not developing network recycling channels, the single-platform model of developing network recycling channels relying on one platform, and the dual-platform model of developing network recycling channels relying on two platforms. These three models correspond to the different commercial patterns of remanufacturers in actual operation management, and the traditional reverse supply chain is corresponding to the basic model when remanufacturers do not expand online channels. When a remanufacturer attempts to establish direct contact with consumers and gain more direct information, it is often realized through online recycling platforms. Remanufacturers can choose to invest the limited resources in one, two or even more platforms to expand the recycling channels. On the one hand, the limited resources will be dispersed as more platforms are engaged, which will significantly lessen the control of the remanufacture over a single platform, and the reduction of resources invested in a single platform will lead to a decrease in their recycling propaganda and the passenger flow. On the other hand, considering the independence of the online platform, the increase in the number of recycling platforms would extend business opportunities of the

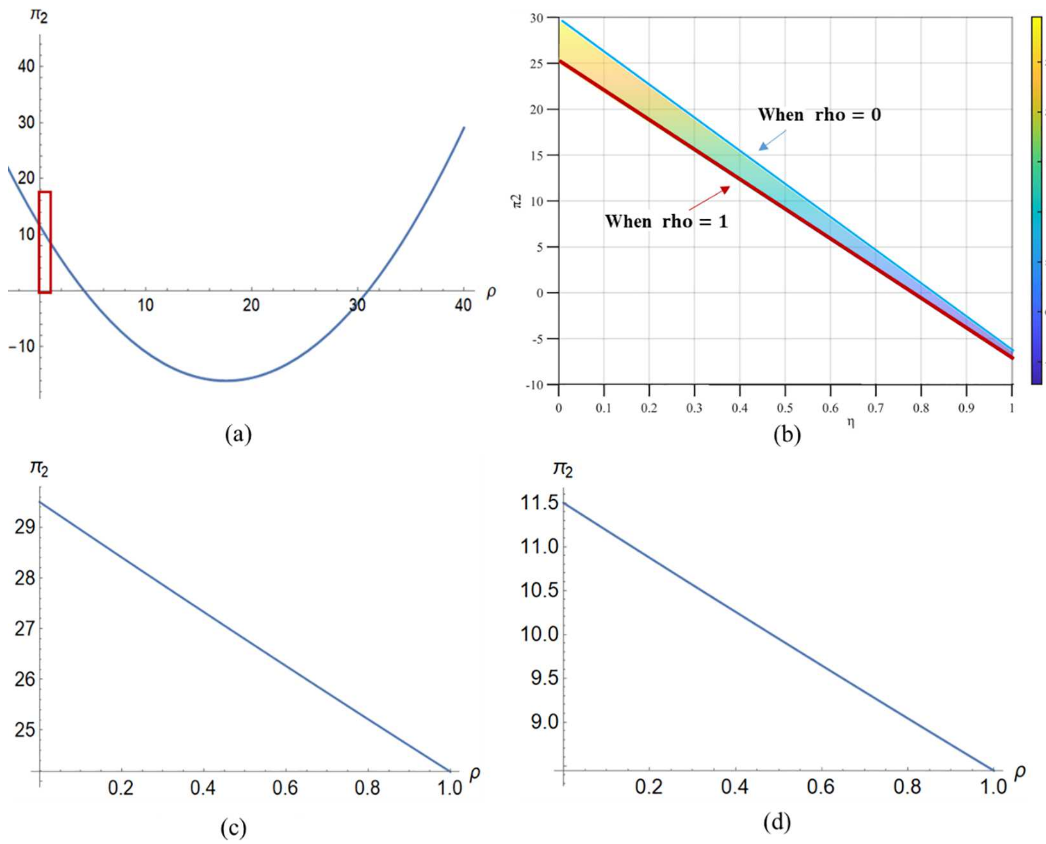

FIGURE 13. The relationship of "$\pi_2 - \eta - \rho$". (a) π_2 when $\eta = 0$ and $-8 \leq \rho \leq 40$. (b) π_2 when $\rho = 0\&1$ and $0 \leq \eta \leq 1$. (c) π_2 when $\eta = 0$ and $0 \leq \rho \leq 1$. (d) π_2 when $\eta = 0.82$ and $0 \leq \rho \leq 1$.

remanufacturer and attract more people to recycle. As a result, when remanufacturers expand online recycling channels, they must strategically allocate their resources since, as findings of this research showed not the more platforms you rely on, the better.

6.1. Profits of the remanufacturer under three models

The complexity of the profit function makes it challenging to contrast the three different business structures using mathematical analysis. As a result, this section employs the numerical simulation method to more intuitively compare the three models *via* different profit trends presented by parameter changes.

To simplify the calculation and avoid affecting the final result, defined b as 1. In the Stackelberg game, solutions of p_{01}, p_{02}, p_1 in the second stage have been substituted into the profit according to the reverse solution method. Based on the previous calculation, there is a maximum point in the basic model. However, considering the possibility that the maximum point of the remanufacturer's profit may exceed the critical range under the single-platform and double-platform structure, it is impossible to directly use the maximum point (w, π_2) in the first stage for comparison.

To put it another way, when assigning different values to parameters, the intermediate function of "$\pi_2 - w$" between the first and second stage is intercepted and compared. The profits of the remanufacturer in three models have been shown in Figure 14, in accordance with values of nine groups in Table 5.

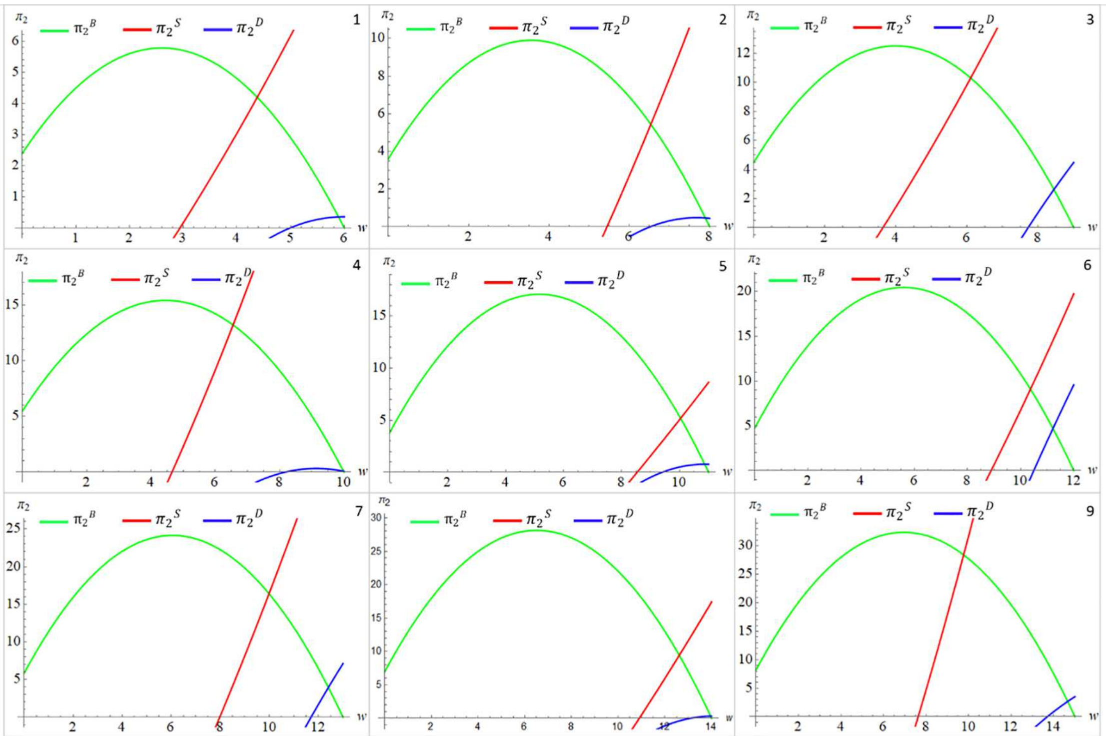

FIGURE 14. Relationships of "$\pi_2 - w$" under three structures.

TABLE 5. The profit of remanufacturer under three supply chain structures (9 groups).

	Index									Basic model		Single platform model	Double platform model
	v	ρ	a	γ	γ_1	γ_2	γ_3	λ	η	π_2^B (The Green Line)	$\pi_2^{B^*}$	π_2^S (The Red Line)	π_2^D (The Blue Line)
1	6	0.7	0.8	0.6	0.4	0.5	0.7	0.6	0.5	$2.4 + 2.6w - 0.5w^2$	5.78	$-6.88 + 1.96w + 0.13w^2$	$-12.54 + 4.31w - 0.36w^2$
2	8	0.8	0.9	0.7	0.6	0.4	0.5	0.4	0.6	$3.6 + 3.55w - 0.5w^2$	9.90	$-20.76 + 2.83w + 0.18w^2$	$-20.76 + 5.53w - 0.36w^2$
3	9	0.6	1	0.6	0.5	0.7	0.6	0.3	0.4	$4.5 + 4w - 0.5w^2$	12.5	$-12.24 + 2.90w + 0.13w^2$	$-42.23 + 7.17w - 0.22w^2$
4	10	0.4	1.1	0.8	0.4	0.6	0.5	0.4	0.4	$5.5 + 4.45w - 0.5w^2$	15.40	$-24.66 + 4.14w + 0.25w^2$	$-28.93 + 6.40w - 0.35w^2$
5	11	0.8	0.7	0.4	0.4	0.6	0.5	0.6	0.6	$3.85 + 5.15w - 0.5w^2$	17.11	$-25.23 + 2.53w + 0.05w^2$	$-41.69 + 7.82w - 0.36w^2$
6	12	0.5	0.8	0.6	0.6	0.7	0.6	0.8	0.6	$4.8 + 5.6w - 0.5w^2$	20.48	$-42.63 + 3.64w + 0.13w^2$	$-90.85 + 10.94w - 0.19w^2$
7	13	0.8	0.9	0.7	0.7	0.6	0.5	0.6	0.5	$5.85 + 6.05w - 0.5w^2$	24.15	$-50.77 + 4.93w + 0.18w^2$	$-95.85 + 10.65w - 0.21w^2$
8	14	0.6	1	0.5	0.6	0.5	0.4	0.4	0.6	$7 + 6.5w - 0.5w^2$	28.13	$-48.39 + 3.52w + 0.08w^2$	$-68.03 + 9.73w - 0.35w^2$
9	15	0.4	1.1	0.9	0.8	0.4	0.4	0.5	0.4	$8.25 + 6.95w - 0.5w^2$	32.40	$-76.85 + 7.56w + 0.33w^2$	$-90.54 + 10.17w - 0.26w^2$

When w is small, the benchmark situation brings more profits to the remanufacturer compared to other patterns. With the gradual increase of w, the profit of the remanufacturer in single platform mode exceeds the benchmark. Only when w is close to v can the dual-platform model become the highest profit structure among the three. The analysis shows that the three models are not absolutely good or bad, but show different trends with the changes of basic parameters (such as the profit allocation proportion η, consumer recycling preference ρ, etc.). Remanufacturers should consider the actual situation when deciding whether enter into recycling channels or not.

Although none of the three models has clear advantages or disadvantages, they all exhibit some common rules. It is unnecessary to expand online recycling channels when a remanufacturer acquires e-waste from the individual recycler at a low payment. This is because the benefits of the remanufacturer from processing,

TABLE 6. The profit of remanufacturer under three supply chain structures (19 groups).

		Index									Basic model		Single Platform model	Double platform model
		v	ρ	a	γ	γ_1	γ_2	γ_3	λ	η	π_2^B (The Green Line)	$\pi_2^{B^*}$	π_2^S (The Red Line)	π_2^D (The Blue Line)
Base	1	6	0.7	0.8	0.6	0.4	0.5	0.6	0.6	0.5	$2.40 + 2.6w - 0.5w^2$	5.78	$-6.88 + 1.96w + 0.13w^2$	$-10.47 + 4.03w - 0.38w^2$
(1)	2	6	0.7	0.8	0.6	0.4	0.5	0.7	0.6	0.7	$2.40 + 2.6w - 0.5w^2$	5.78	$-11.09 + 1.77w + 0.13w^2$	$-11.11 + 4.22w - 0.39w^2$
	3	6	0.7	0.8	0.6	0.4	0.5	0.7	0.6	0.4	$2.40 + 2.6w - 0.5w^2$	5.78	$-4.78 + 2.06w + 0.13w^2$	$-10.14 + 3.93w - 0.37w^2$
(2)	4	6	0.7	0.8	0.6	0.4	0.5	0.6	0.9	0.5	$2.40 + 2.6w - 0.5w^2$	5.78	$-6.88 + 1.96w + 0.13w^2$	$-10.48 + 4.03w - 0.38w^2$
	5	6	0.7	0.8	0.6	0.4	0.5	0.6	0.2	0.5	$2.40 + 2.6w - 0.5w^2$	5.78	$-6.88 + 1.96w + 0.13w^2$	$-10.44 + 4.02w - 0.38w^2$
(3)	6	6	0.7	0.8	0.6	0.4	0.5	0.7	0.6	0.5	$2.40 + 2.6w - 0.5w^2$	5.78	$-6.88 + 1.96w + 0.13w^2$	$-12.54 + 4.31w - 0.36w^2$
	7	6	0.7	0.8	0.6	0.4	0.5	0.4	0.6	0.5	$2.40 + 2.6w - 0.5w^2$	5.78	$-6.88 + 1.96w + 0.13w^2$	$-6.46 + 3.64w - 0.40w^2$
(4)	8	6	0.7	0.8	0.6	0.4	0.7	0.6	0.6	0.5	$2.40 + 2.6w - 0.5w^2$	5.78	$-6.88 + 1.96w + 0.13w^2$	$-15.76 + 4.47w - 0.29w^2$
	9	6	0.7	0.8	0.6	0.4	0.4	0.6	0.6	0.5	$2.40 + 2.6w - 0.5w^2$	5.78	$-6.88 + 1.96w + 0.13w^2$	$-8.22 + 3.86w - 0.41w^2$
(5)	10	6	0.7	0.8	0.6	0.7	0.5	0.6	0.6	0.5	$2.40 + 2.6w - 0.5w^2$	5.78	$-6.88 + 1.96w + 0.13w^2$	$-18.58 + 4.77w - 0.24w^2$
	11	6	0.7	0.8	0.6	0.2	0.5	0.6	0.6	0.5	$2.40 + 2.6w - 0.5w^2$	5.78	$-6.88 + 1.96w + 0.13w^2$	$-6.30 + 3.71w - 0.43w^2$
(6)	12	6	0.7	0.8	0.8	0.4	0.5	0.6	0.6	0.5	$2.40 + 2.6w - 0.5w^2$	5.78	$-10.42 + 2.56w + 0.25w^2$	$-10.47 + 4.03w - 0.38w^2$
	13	6	0.7	0.8	0.3	0.4	0.5	0.6	0.6	0.5	$2.40 + 2.6w - 0.5w^2$	5.78	$-2.21 + 1.16w + 0.03w^2$	$-10.47 + 4.03w - 0.38w^2$
(7)	14	6	0.7	1.2	0.6	0.4	0.5	0.6	0.6	0.5	$3.6 + 2.4w - 0.5w^2$	6.48	$-5.28 + 1.68w + 0.13w^2$	$-9.36 + 3.85w - 0.38w^2$
	15	6	0.7	0.6	0.6	0.4	0.5	0.6	0.6	0.5	$1.80 + 2.7w - 0.5w^2$	5.44	$-7.66 + 2.10w + 0.13w^2$	$-11.01 + 4.11w - 0.38w^2$
(8)	16	6	0.8	0.8	0.6	0.4	0.5	0.6	0.6	0.5	$2.40 + 2.6w - 0.5w^2$	5.78	$-7.07 + 2.01w + 0.13w^2$	$-10.61 + 4.05w - 0.38w^2$
	17	6	0.4	0.8	0.6	0.4	0.5	0.6	0.6	0.5	$2.40 + 2.6w - 0.5w^2$	5.78	$-6.31 + 1.81w + 0.13w^2$	$-10.03 + 3.95w - 0.38w^2$
(9)	18	10	0.7	0.8	0.6	0.4	0.5	0.6	0.6	0.5	$4 + 4.6w - 0.5w^2$	14.58	$-23.5 + 3.28w + 0.13w^2$	$-31.46 + 6.94w - 0.38w^2$
	19	4	0.7	0.8	0.6	0.4	0.5	0.6	0.6	0.5	$1.6 + 1.6w - 0.5w^2$	2.88	$-2.2 + 1.3w + 0.13w^2$	$-4.16 + 2.57w - 0.38w^2$

remanufacturing and secondary sales as an upstream enterprise are greater than those from expanding online recycling channels. On the contrary, if remanufacturers need to pay more to obtain the e-waste collected from individual recyclers, the profit of remanufacturers under the basic model will show a downward trend. At this point, the single-platform structure is the rational choice, the profit of remanufacturers in which mode will be greater than the basic mode. It can be seen from Figure 14 that compared with the basic state, the development of single platform can even bring 2–3 times increase to the profit of remanufacturers under certain circumstances. Reasonable parameters can significantly increase the profit of the remanufacturer. With the increasing of $w(w \to v)$, it will be more desirable for remanufacturers to expand two online recycle channels, as shown in Figure 14. Therefore, only online channel expansion under certain circumstances can bring more profits to the remanufacturer, which is affected by varies factors, such as the profit allocation proportion from remanufactures to platforms, the recycling preference and the price sensitivity of consumers, etc.

6.2. Influence of parameters in three models

Nine control groups of Table 6, have been set up to further explore the influences of parameters on the remanufacturer under different mode more effectively, as shown in Figures 15–17.

Figure 15. (1) shows the profit of the remanufacturer while the profit allocation proportion η is 0.7, 0.5, and 0.4. With the decrease of η, the profit of the remanufacturer under the single-platform mode will reach a higher value at the same w, which will occupy a greater advantage, but the dual-platform model is not obviously affected by the η. It is easy to understand that when remanufacturers need to allocate less benefits to recycling platforms, they tend to adopt a single-platform recycling model. With the situation that remanufacturers need to pay more money to get ewastes from individual recyclers, they will be more inclined to expand their own online recycling channels through platforms. With the increase of η and w, this trend will become more and more obvious.

Figure 15. (2) are generated by varying the market share of the two platforms in the online recycling, in the circumstance of which the profit of the remanufacturer in the dual-platform mode will not change noticeably because of the market share of two platforms and can be disregarded. Figure 15. (3) shows the profit of the remanufacturer is positively related to the competition coefficient of two platforms in three models. Dual-platform mode is better when w is small and there is not much competition between the two platforms. It is simple to understand that recycling participants are all economically rational hoping to earn more money through ewaste recycling. Therefore, when competition among platforms for online recycling is fierce, the recy-

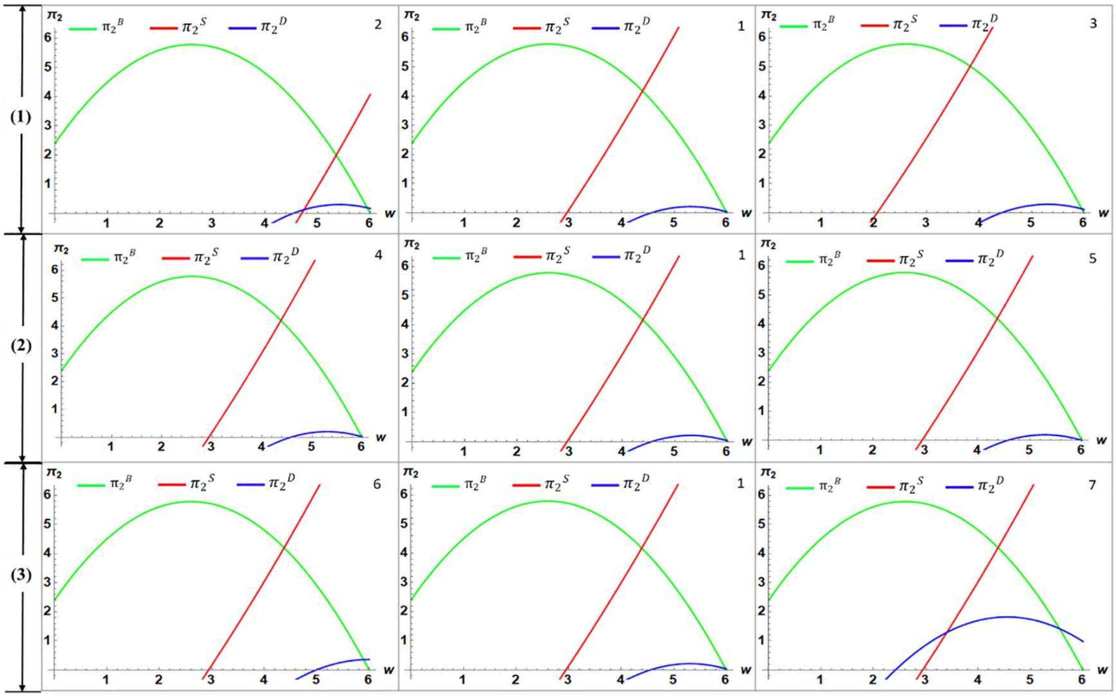

FIGURE 15. Group (1)–(2)–(3) of "$\pi_2 - w$" under three modes.

cling price will be higher, which raises the online recycling expenses of remanufacturers, and this trend becomes more obvious as w decreases. This reflects the individual economic rationality as well as the negative economic externalities brought about by the competition between two platforms to other firms in the supply chain.

When the competition coefficient between of platforms and individual recyclers decreases, profits of the remanufacturer in groups 4 and 5 exhibit a similar trend as in Group 3. In the dual-platform recycling structure, the fiercer the competition between the three recycling channels, the lower the profit of the remanufacturer. It's concluded that the low competitive recycling market contributes to the profit improvement of the remanufacturer. Corresponding to economic theories, "Price competition" is an unavoidable economic principle in market operation, which has long been valued by commodity producers and operators, and when it comes to competition, people will think of price reduction. Price reduction, because it is easy to imitate, will easily lead to retaliation from competitors, resulting in both losses, and will ultimately fail to improve economic efficiency, resulting in the proliferation of price competition. Price competition may be important in some circumstances, but instead of competing solely on price, the long-term goal of the enterprise is to figure out how to take effective measures to survive and thrive in the market based on their restricted resources and surroundings.

The control group (6) shows the influence trend of the price competition coefficient between recycling platform and individual recyclers on the profit of remanufacturers in a single platform. The impact of w on remanufacturers' profits will be lessened when the price competitiveness coefficient declines. The essential value w^* for the remanufacturer to decide to forgo the benchmark and create a single-platform recycling structure steadily rises as the price competitiveness coefficient drops. When remanufacturers have to pay more to buy electronic waste from individual recyclers, they will be more motivated to create more controllable recycling channels to make up for their losses. Additionally, this trend will become more pronounced as competition between platform recycling and individual recycling increases, which is also consistent with the results of this study. Firms can adjust their decisions to avoid unnecessary price competition.

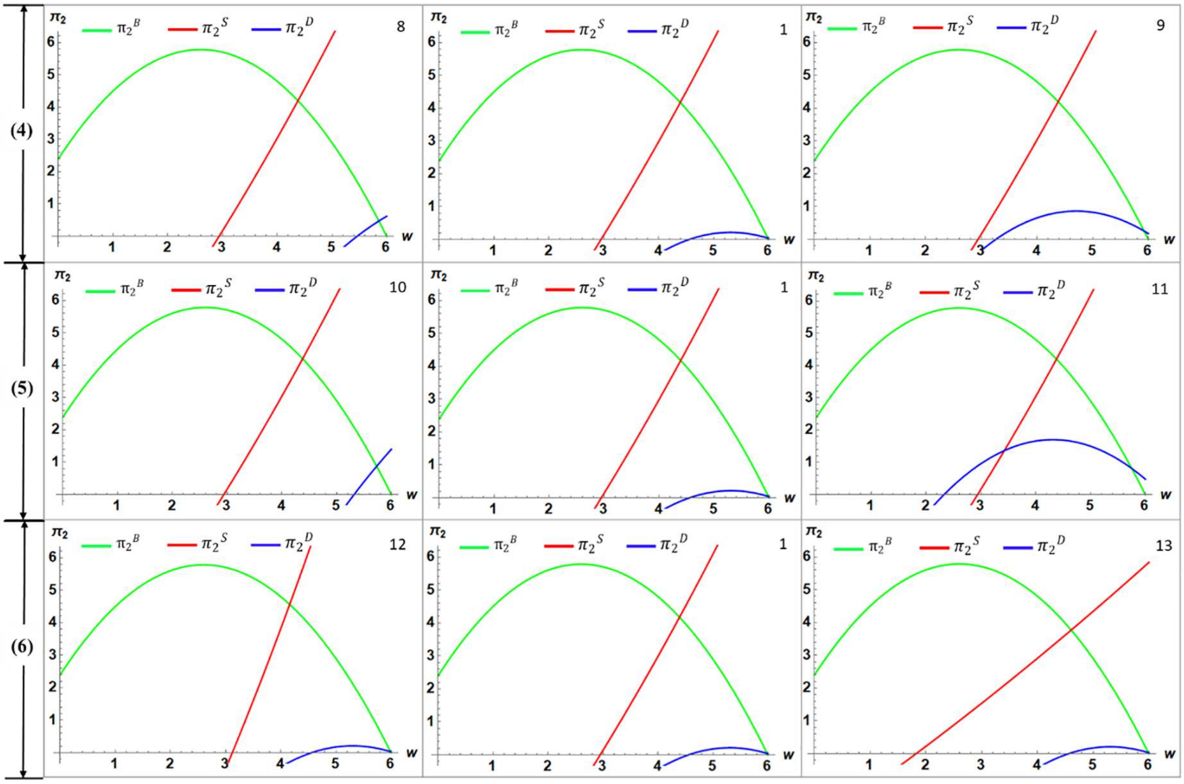

FIGURE 16. Graph (4)–(5)–(6) of "$\pi_2 - w$" under three modes.

The group (7) depicts when the recycling market capacity is reduced, the profit of the remanufacturer has a slight downward trend in the whole. The group (8) depicts when consumers are more likely to recycle ewastes online, as shown in Figure 17. (8), the profit of the remanufacturer under the singleplatform mode and the dualplatform mode will increase slightly. Thus, the recycling mode choice of the remanufacturer is not significantly affected by the consumer preference. The group (9) shows the influence of the unit income brought by the recycling-processing-remanufacturing process to the remanufacturer profits, which is consistent with the actual situation that the greater the unit income from remanufacturing, the greater the overall profit. That is the profit of the remanufacturer rise significantly as v increases. When the unit income v is large enough, the profit under the benchmark model and the single platform model begin to completely supersede the dual platform model, and the dual platform model no longer has any advantage.

The numerical simulation shows that remanufacturers recycling ewaste *via* dual platforms is not dominant, unless the value of w can approach v infinitely. The maximum of w in the illustration corresponds to v, but in practice, w that the remanufacturer pays the specific recycler to acquire their ewaste is usually far less than the revenue v that will be gained by selling electronic waste twice, because remanufacturers must pay extra labor, technology, and time for the treatment, remanufacturing, and secondary sale of electronic waste, costs of which will be reflected in the difference between v and w. Due to the objective difference between v and w, it is more advantageous for remanufacturers to select the benchmark model and the singleplatform model in practical application. The dual-platform model will increase management costs in this reverse supply chain and provide no additional benefits in most cases. This phenomenon can be explained by the dispersion of resources. When remanufacturers recycle through multiple platforms, its available resources will be distributed and the resources invested in a single platform will be reduced, which limits the benefits that a single platform can provide to

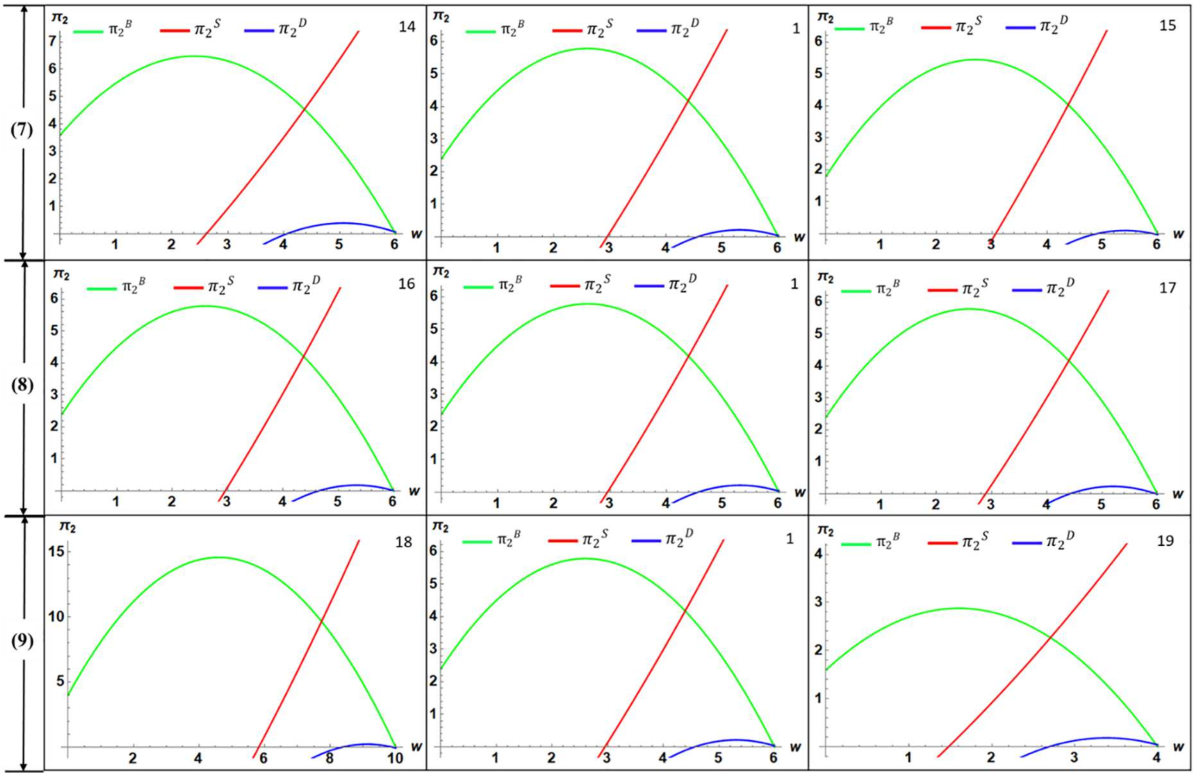

FIGURE 17. Graph (4)–(5)–(6) of "$\pi_2 - w$" under three modes.

remanufacturers, and it is difficult to play the full role of the single platform in this scenario. The conclusion will promote remanufacturers to think whether to pursue the breadth of multi-platform and rationally allocate resources in depth.

7. Conclusions

The stock and increment of electronic waste have been increasing year by year, while the efficiency of recycling and disposal has not shown significant improvement. With the widespread application of the Internet, online platforms for recycling can significantly enhance recycling efficiency. The combination of online and offline recycling is gradually becoming a common choice for remanufacturers in the recycling process. In order to study the impact of online recycling methods and the number of recycling platforms on the profits of remanufacturers to help them choose better business models, this article establishes basic models, single-platform models, and dual-platform models based on the background of electronic waste recycling. It investigates the trend of the impact of market environment changes under different business structures on the profits of remanufacturers and draws some interesting conclusions.

The study finds that in a single-platform model, setting a lower profit-sharing ratio for the recycling platform does not necessarily leave higher profits for the remanufacturer, but the opposite is true in a dual-platform model. Over multiple decision-making cycles, adjusting decisions too quickly may not necessarily benefit the stability of the recycling supply chain system. The direct payment price that remanufacturers pay to individual recyclers for waste is closely related to whether they choose to expand online recycling channels. Only when remanufacturers offer unlimited concessions to individual recyclers is the dual-platform model superior to the single-platform model, but the likelihood of this scenario is very small.

"*Going too far is as bad as not going far enough.*" While making business decisions, remanufacturers should make reasonable predictions based on the current situation rather than blindly following trends and pursuing excessive scale. Reasonable decisions can increase observable profits, reduce management risks, and contribute to long-term development. In practical business management, upstream leading companies should expand their business structure rationally according to market layout, rather than pursuing excessive market share. Some remanufacturing companies choose to collaborate with multiple recyclers to avoid recycling price discrimination in the recycling market and to reduce risks and pursue a broader business layout. However, in this case, upstream companies also incur higher management costs. In reality, companies need to maintain customer relationships, and the more collaborators they have, the more effort they will need to put in. Therefore, is it always the case that the more collaborating recyclers there are, the higher the profits for remanufacturers? Not necessarily. This study addresses this challenging issue and provides some interesting conclusions different from conventional wisdom. The conclusions of this study can help upstream remanufacturing companies better decide on the number of collaborating recyclers to achieve higher profits.

Furthermore, when market changes occur, is it advantageous for companies to adjust their business decisions promptly to achieve stable profits? Not necessarily. In our understanding, the response of companies to sudden situations should be as timely as possible. However, the conclusions of this study show that when market changes occur alternately between two cycles, decision adjustments made by companies too quickly (reaction speed) are not conducive to the stability of the supply chain and may lead to the occurrence of chaos. Both too fast and too slow decision adjustments and response speeds are detrimental to the stable development of companies. Companies need to formulate emergency plans more suitable for their own characteristics to ensure that decision adjustments resist the risk impact of sudden events to the maximum extent when market changes occur between two cycles. The conclusions of this study have important reference value for the selection of business structures by remanufacturers and the maintenance of stability in responding to market changes in reverse supply chains. Companies can make more efficient channel structure formulations and decision adjustment strategies based on the conclusions of this study.

However, it is important to acknowledge several limitations that persist within this study. First, this study is based on complete information, but in reality, the information between upstream and downstream enterprises is often asymmetric. That is, in reality, if recyclers or remanufacturers conceal their actual recycling amounts, the optimal pricing strategies for both parties would likely differ, potentially reducing the likelihood of cooperation. Additionally, to simplify the model, the challenge of production and marketing imbalances was overlooked. When output exceeds sales volume, costs rise due to inventory backlogs, which could impact profits. Finally, the decision of channel expansion under asymmetric information and the recycling strategy under different structures considering inventory cost can be included in future research.

Appendix A.

A.1.

There exists the maximum value about π_1.

$$\frac{\mathrm{d}\pi_1}{\mathrm{d}p_1} = -a + bw - 2bp_1 \to \frac{\mathrm{d}^2\pi_1}{\mathrm{d}p_1^2} = -2b < 0; \quad \frac{\mathrm{d}\pi_1}{\mathrm{d}p_1} = 0 \to p_1^* = \frac{bw-a}{2b}\cdot$$

Substitute p_1^* into π_2 to get: $\pi_2 = av - aw + bp_1 v - bp_1 w = \frac{av-aw+bwv-bw^2}{2}$. According to $\frac{\mathrm{d}^2\pi_2}{\mathrm{d}w^2} = -b < 0$, we can know there exists the maximum value about π_2.

$$\frac{\mathrm{d}\pi_2}{\mathrm{d}w} = \frac{-a+bv-2bw}{2} = 0 \to w^* = \frac{-a+bv}{2b}\cdot$$

Then, we can get: $p_1^* = \frac{bw^*-a}{2b} = \frac{-3a+bv}{4b}, \pi_1^* = (w^* - p_1^*)(a + bp_1^*) = \frac{(bv+a)^2}{16b}, \pi_2^* = (v - w^*)(a + bp_1^*) = \frac{(bv+a)^2}{8b}$.

A.2.

First, the profit function of each recycler is examined, with the supposition being that both are Nash equilibrium games. According to "$\frac{\partial \pi_0}{\partial p_0} = \eta v - \rho a\eta - 2\eta p_0 + \gamma\eta p_1, \frac{\partial^2 \pi_0}{\partial p_0^2} = -2\eta < 0$", the profit function of the recycling platform shows a trend of first rising and then falling, and there is an extreme point. According to "$\frac{\partial \pi_1}{\partial p_1} = w - (1-\rho)a - 2p_1 + \gamma p_0, \frac{\partial^2 \pi_1}{\partial p_1^2} = -2 < 0$", the profit function of individual recyclers also shows a trend of rising first and then falling, and there is an extreme point. The simultaneous derivative function is solved:

$$\begin{cases} \frac{\partial \pi_0}{\partial p_0} = \eta(v - \rho a - 2p_0 + \gamma p_1) = 0 \\ \frac{\partial \pi_1}{\partial p_1} = w - (1-\rho)a - 2p_1 + \gamma p_0 = 0 \end{cases} \rightarrow \begin{cases} p_0^* = \frac{(1-\rho)a\gamma + 2\rho a - 2v - w\gamma}{\gamma^2 - 4} \\ p_1^* = \frac{-2w + 2(1-\rho)a + \rho a\gamma - v\gamma}{\gamma^2 - 4}. \end{cases}$$

In the second stage, the remanufacturer should set the optimal recovery purchase price w and profit share η to maximize its profits. Substituting the p_0^*, p_1^* into the π_2 function to get the profit of the remanufacturer:

$$\begin{aligned} \pi_2 &= (v-w)q_1 + v(1-\eta)q_0 - p_0 q_0 = (v-w)((1-\rho)a + p_1 - \gamma p_0) + v(1-\eta)(\rho a + p_0 - \gamma p_1) - p_0(\rho a + p_0 - \gamma p_1) \\ &= \frac{1}{(\gamma^2-4)^2}\left[\gamma\begin{pmatrix} (1-\rho)a\gamma(-2w + 2(1-\rho)a + \rho a\gamma - v\gamma) + 2\rho a(-2w + 2(1-\rho)a + \rho a\gamma - v\gamma) \\ -2v(-2w + 2(1-\rho)a + \rho a\gamma - v\gamma) - w\gamma(-2w + 2(1-\rho)a + \rho a\gamma - v\gamma) \end{pmatrix}\right. \\ &\quad \left. - ((1-\rho)a\gamma + 2\rho a - 2v - w\gamma)^2 \right] \\ &\quad + \frac{1}{\gamma^2-4}\left[\begin{matrix} (a\gamma - \rho a\gamma)(v - v\eta - v\gamma + w\gamma - \rho a) + 2\rho a(v - v\eta - v\gamma + w\gamma - \rho a) - 2v(v - v\eta - v\gamma + w\gamma - \rho a) \\ -(w\gamma v - w\gamma v\eta - w\gamma^2 v + w^2\gamma^2 - w\gamma\rho a) - 2w + 2(1-\rho)a + \rho a\gamma - v\gamma \end{matrix}\right] \\ &\quad + (av - aw + a\rho w - \rho av\eta) \end{aligned}$$

$$\begin{aligned} \frac{\partial \pi_2}{\partial w} &= \frac{1}{(\gamma^2-4)^2}\left(2w\gamma^2 - 2a\gamma^2 + 2\rho a\gamma^2 - \rho a\gamma^3 + v\gamma^3\right) + \frac{1}{\gamma^2-4}\left(a\gamma^2 - \rho a\gamma^2 + 3\rho a\gamma - 3v\gamma + \gamma v\eta + \gamma^2 v - 2w\gamma^2 - 2\right) \\ &\quad - a + a\rho \end{aligned}$$

$$\frac{\partial^2 \pi_2}{\partial w^2} = \frac{10\gamma^2 - 2\gamma^4}{(\gamma^2-4)^2}; \frac{\partial^2 \pi_2}{\partial w \partial \eta} = \frac{\gamma v}{\gamma^2-4}; \frac{\partial \pi_2}{\partial \eta} = \frac{v(-a\gamma + \rho a\gamma - 2\rho a + 2v + w\gamma)}{\gamma^2-4} - \rho av; \frac{\partial^2 \pi_2}{\partial \eta^2} = 0; \frac{\partial^2 \pi_2}{\partial \eta \partial w} = \frac{v\gamma}{\gamma^2-4}.$$

Get the Hesse matrix of π_2 about w and η.

$$H_1 = \begin{bmatrix} \frac{\partial^2 \pi_2}{\partial w^2} & \frac{\partial^2 \pi_2}{\partial w \partial \eta} \\ \frac{\partial^2 \pi_2}{\partial \eta \partial w} & \frac{\partial^2 \pi_2}{\partial \eta^2} \end{bmatrix} = \begin{bmatrix} \frac{10\gamma^2 - 2\gamma^4}{(\gamma^2-4)^2} & \frac{\gamma v}{\gamma^2-4} \\ \frac{v\gamma}{\gamma^2-4} & 0 \end{bmatrix}.$$

The sequence principal sub-formula is:

$$D_1 = \frac{10\gamma^2 - 2\gamma^4}{(\gamma^2-4)^2} = \frac{2\gamma^2(5-\gamma^2)}{(\gamma^2-4)^2} > 0; \quad D_2 = \begin{vmatrix} \frac{10\gamma^2 - 2\gamma^4}{(\gamma^2-4)^2} & \frac{\gamma v}{\gamma^2-4} \\ \frac{v\gamma}{\gamma^2-4} & 0 \end{vmatrix} = -\left(\frac{\gamma v}{\gamma^2-4}\right)^2 < 0.$$

The Hesse matrix is indefinite and there is no extreme point.

A.3.

The second stage of the reverse solution method is the decision of the recycling platform and individual recyclers. To begin, the profit functions (3) - (5) of the recycling platform and individual recyclers are examined, with the assumption that they are Nash equilibrium games.

$$\pi_{01} = (v - p_{01})(\rho\lambda a + bp_{01} - \gamma_3 p_{01} - \gamma_1 p_1)\eta$$

$$\begin{aligned}
\pi_{02} &= (v-p_{02})q_{02}\eta = (v-p_{02})(\rho(1-\lambda)a + bp_{02} - \gamma_3 p_{01} - \gamma_2 p_1)\eta \\
\pi_1 &= (w-p_1)q_1 = (w-p_1)[(1-\rho)a + bp_1 - \gamma_1 p_{01} - \gamma_2 p_{02}] \\
\frac{\partial \pi_{01}}{\partial p_{01}} &= \eta v b - \rho\lambda a\eta - 2b\eta p_{01} + \eta\gamma_3 p_{02} + \eta\gamma_1 p_1; \\
\frac{\partial^2 \pi_{01}}{\partial p_{01}^2} &= -2b\eta < 0;\quad \frac{\partial \pi_{02}}{\partial p_{02}} = \eta v b - \rho(1-\lambda)a\eta - 2bp_{02}\eta + \eta\gamma_3 p_{01} + \eta\gamma_2 p_1; \\
\frac{\partial^2 \pi_{02}}{\partial p_{02}^2} &= -2b\eta < 0;\quad \frac{\partial \pi_1}{\partial p_1} = bw - (1-\rho)a - 2bp_1 + \gamma_1 p_{01} + \gamma_2 p_{02};\quad \frac{\partial^2 \pi_1}{\partial p_1^2} = -2b < 0.
\end{aligned}$$

There is a maximum point in the profit functions of platform 1, platform 2, and individual recyclers, which all exhibit a trend of rising first and then falling.

$$\begin{cases}
\frac{\partial \pi_{01}}{\partial p_{01}} = \eta v b - \rho\lambda a\eta - 2b\eta p_{01} + \eta\gamma_3 p_{02} + \eta\gamma_1 p_1 = 0 \\
\frac{\partial \pi_{02}}{\partial p_{02}} = \eta v b - \rho(1-\lambda)a\eta - 2bp_{02}\eta + \eta\gamma_3 p_{01} + \eta\gamma_2 p_1 = 0 \quad \rightarrow \\
\frac{\partial \pi_1}{\partial p_1} = bw - (1-\rho)a - 2bp_1 + \gamma_1 p_{01} + \gamma_2 p_{02} = 0
\end{cases}$$

$$\begin{cases}
p_{01} = \frac{\gamma_2^2(a\lambda\rho - bv) + 2b(\gamma_3(a(\lambda-1)\rho + bv) + 2b(bv - a\lambda\rho)) + \gamma_1(\gamma_2(a(\lambda-1)\rho + bv) + 2b(a(\rho-1) + bw)) + \gamma_3\gamma_2(a(\rho-1) + bw)}{8b^3 - 2b\gamma_1^2 - 2b\gamma_2^2 - 2b\gamma_3^2 - 2\gamma_1\gamma_2\gamma_3} \\
p_{02} = \frac{\gamma_1^2(-(a(\lambda-1)\rho + bv)) + \gamma_1(\gamma_2(bv - a\lambda\rho) + \gamma_3(a(\rho-1) + bw)) + 2b(\gamma_3(bv - a\lambda\rho) + 2b(a(\lambda-1)\rho + bv) + \gamma_2(a(\rho-1) + bw))}{8b^3 - 2b\gamma_1^2 - 2b\gamma_2^2 - 2b\gamma_3^2 - 2\gamma_1\gamma_2\gamma_3} \\
p_1 = \frac{\left(4b^2 - \gamma_3^2\right)(a(\rho-1) + bw) + \gamma_1(\gamma_3(a(\lambda-1)\rho + bv) + 2b(bv - a\lambda\rho)) + \gamma_2(\gamma_3(bv - a\lambda\rho) + 2b(a(\lambda-1)\rho + bv))}{8b^3 - 2b\gamma_1^2 - 2b\gamma_2^2 - 2b\gamma_3^2 - 2\gamma_1\gamma_2\gamma_3}.
\end{cases}$$

Bring (5-5) into (5-4) to get the profit function of the remanufacturer.

$$\begin{aligned}
\pi_2 = &\frac{1}{4\left(b\left(-4b^2 + \gamma_2^2 + \gamma_3^2\right) + b\gamma_1^2 + \gamma_2\gamma_3\gamma_1\right)^2} \\
&\times \left(b \left(\begin{array}{l}
-2\left(4b^3 - b\gamma_1^2 - b\gamma_2^2 - b\gamma_3^2 - \gamma_1\gamma_2\gamma_3\right)(v-w)\left(\begin{array}{l} -\left(4b^2 - \gamma_3^2\right)(a(-\rho) + a + bw) + \gamma_2(\gamma_3(bv - a\lambda\rho) + 2b(a(\lambda-1)\rho + bv)) \\ +\gamma_1(2b(bv - a\lambda\rho) + \gamma_3(a(\lambda-1)\rho + bv + 2\gamma_2 w)) + 2b\gamma_1^2 w + 2b\gamma_2^2 w \end{array} \right) \\
-(\eta-1)\left(\gamma_2^2(a\lambda\rho + bv) + 2b\left(\begin{array}{l} \gamma_3(a(\lambda-1)\rho + bv) \\ -2b(a\lambda\rho + bv) + \gamma_3^2 v \end{array} \right) + \gamma_1\left(\begin{array}{l} \gamma_2(a(\lambda-1)\rho + bv + 2\gamma_3 v) \\ +2b(a(\rho-1) + bw) \end{array} \right) + \gamma_2\gamma_3(a(\rho-1) + bw) + 2b\gamma_1^2 v\right)^2 \\
-(\eta-1)\left(\gamma_1^2(bv - a(\lambda-1)\rho) + \gamma_1(\gamma_2(-a\lambda\rho + bv + 2\gamma_3 v) + \gamma_3(a(\rho-1) + bw)) + 2b\left(\begin{array}{l} \gamma_3(bv - a\lambda\rho) - 2b(-a\lambda\rho + a\rho + bv) \\ +\gamma_2(a(\rho-1) + bw) + \gamma_2^2 v + \gamma_3^2 v \end{array} \right)\right)^2
\end{array} \right) \right).
\end{aligned}$$

Get the Hesse-matrix H_1 of π_2 about $w-\eta$ and its even-order sequence principal formula. The Hesse matrix is an indefinite matrix.

$$H_1 = \begin{bmatrix} \frac{\partial^2 \pi_2}{\partial w^2} & \frac{\partial^2 \pi_2}{\partial w \partial \eta} \\ \frac{\partial^2 \pi_2}{\partial \eta \partial w} & \frac{\partial^2 \pi_2}{\partial \eta^2} \end{bmatrix};\quad D_2 = \begin{vmatrix} \frac{\partial^2 \pi_2}{\partial w^2} & \frac{\partial^2 \pi_2}{\partial w \partial \eta} \\ \frac{\partial^2 \pi_2}{\partial \eta \partial w} & 0 \end{vmatrix} = -\left(\frac{\partial^2 \pi_2}{\partial w \partial \eta}\right)^2 < 0.$$

A.4.

The stability of equilibrium points is tested by solving the Jacobian matrix of each equilibrium point. The calculation process of Jacobian matrix is as follows: For the dynamic game equation obtained when $p_{i,t+1} = p_{i,t}, w_{t+1} = w_t$, the first-order partial derivatives of decision variables (p_0, p_1, w) are solved for each line of the equation. The Jacobian matrix of system is shown as follows.

$$J = \begin{bmatrix} J_{11} & \gamma\eta g_0 p_0 & 0 \\ g_1 p_1 \gamma & J_{22} & bg_1 p_1 \\ w\gamma g_2 & -wbg_2 & J_{33} \end{bmatrix} \begin{cases} J_{11} = 1 + g_0\eta(bv - \rho a + \gamma p_1 - 4bp_0) \\ J_{22} = 1 + g_1(wb - (1-\rho)a + \gamma p_0 - 4bp_1) \\ J_{33} = 1 + g_2(-(1-\rho)a - bp_1 + \gamma p_0). \end{cases}$$

Six equilibrium points are substituted into the Jacobian matrix respectively and the stability is judged according to the size of their eigenvalues. If the non-zero eigenvalue is greater than 1, the equilibrium point is unstable. It can be analyzed from economics that the decision-maker is not allowed to choose a decision variable with zero value, so only the completely non-zero equilibrium solution is stable. Next, the stability of Nash equilibrium point E_6 is mainly analyzed, and its Jacobian matrix is:

$$J = \begin{bmatrix} \varphi_1 & \gamma\eta g_0 p_0 & 0 \\ g_1 p_1 \gamma & \varphi_2 & b g_1 p_1 \\ w\gamma g_2 & -wbg_2 & \varphi_3 \end{bmatrix}$$

$$\varphi_1 = 1 + g_0\eta\left(bv - \rho a + \gamma\frac{-2ab + 2ab\rho - a\rho\gamma + b\gamma v}{2b^2-\gamma^2} - 4b_0\frac{-\gamma a - ab\rho + b^2 v + a\rho\gamma}{2b^2-\gamma^2}\right);$$

$$\varphi_2 = 1 + g_1\left[\frac{(-2ab + 2ab\rho - a\rho\gamma + b\gamma v)b}{2b^2-\gamma^2} - (1-\rho)a + \frac{\gamma(-\gamma a - ab\rho + b^2 v + a\rho\gamma)}{2b^2-\gamma^2} - \frac{4b(-2ab + 2ab\rho - a\rho\gamma + b\gamma v)}{2b^2-\gamma^2}\right];$$

$$\varphi_3 = 1 + g_2\left(-(1-\rho)a - b\frac{-2ab + 2ab\rho - a\rho\gamma + b\gamma v}{2b^2-\gamma^2} + \gamma\frac{-\gamma a - ab\rho + b^2 v + a\rho\gamma}{2b^2-\gamma^2}\right);$$

$$\downarrow$$

$$\varphi_1 = 1 + \frac{4\gamma abg_0\eta(1-\rho) + 2ab^2 g_0\eta\rho - 2b^3 v g_0\eta}{2b_0b_1-\gamma^2}; \quad \varphi_2 = 1 + g_1\left(\frac{4ab^2 - 4ab^2\rho + 2ba\rho\gamma - 2b^2\gamma v}{2b^2-\gamma^2}\right); \quad \varphi_3 = 1.$$

The corresponding characteristic equation of the matrix is:

$$\begin{aligned} |\lambda E - J| &= \begin{bmatrix} \lambda-\varphi_1 & -\gamma\eta g_0 p_0 & 0 \\ -g_1 p_1\gamma & \lambda-\varphi_2 & -b_1 g_1 p_1 \\ -w\gamma g_2 & wb_1 g_2 & \lambda-\varphi_3 \end{bmatrix} \\ &= (\lambda-\varphi_1)(\lambda-\varphi_2)(\lambda-\varphi_3) - (\gamma\eta g_0 p_0)(bg_1p_1)(w\gamma g_2) - g_1p_1\gamma(\gamma\eta g_0p_0)(\lambda-\varphi_3) \\ &\quad + (\lambda-\varphi_1)(bg_1p_1)(wbg_2) \\ &= \lambda^3 - (\varphi_1+\varphi_2+\varphi_3)\lambda^2 + (\varphi_1\varphi_2 + \varphi_1\varphi_3 + \varphi_2\varphi_3)\lambda - \eta\gamma^2 g_0g_1p_0p_1\lambda + wb^2 g_1g_2p_1\lambda - \varphi_1\varphi_2\varphi_3 \\ &\quad - \eta\gamma^2 wbg_0g_1g_2p_0p_1 + \eta\gamma^2 g_0g_1p_0p_1\varphi_3 - wg_1g_2p_1b^2\varphi_1. \end{aligned}$$

According to Routh–Hurwitz Stability Criterion, all coefficients in the characteristic equation are not equal to 0 d have the same sign, which is a necessary condition for the stability of the system. Given that the coefficient of λ^3 is greater than zero, the condition of local stability of the equilibrium solution is:

$$\begin{cases} -(\varphi_1+\varphi_2+\varphi_3) > 0 \\ \varphi_1\varphi_2 + \varphi_1\varphi_3 + \varphi_2\varphi_3 - \eta g_0g_1p_0p_1\gamma^2 + wb^2g_1g_2p_1 > 0 \\ -\varphi_1\varphi_2\varphi_3 - \eta\gamma^2 wbg_0g_1g_2p_0p_1 + \eta\gamma^2 g_0g_1p_0p_1\varphi_3 - wg_1g_2p_1b^2\varphi_1 > 0 \end{cases}$$

$$\varphi_1 = 1 + \frac{4\gamma abg_0\eta(1-\rho) + 2ab^2 g_0\eta\rho - 2b^3 v g_0\eta}{2b^2-\gamma^2}; \quad \varphi_2 = 1 + g_1\left(\frac{4ab^2 - 4ab^2\rho + 2ba\rho\gamma - 2b^2\gamma v}{2b^2-\gamma^2}\right); \quad \varphi_3 = 1.$$

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