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Evolutionary game analysis of green innovation in E-commerce closed-loop supply chain WEEE recycling

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A B S T R A C T

The accumulation of waste electrical and electronic equipment (WEEE) has become a critical global issue. E-commerce platforms offer new opportunities for WEEE recycling, making it a subject of interest for researchers. This study focuses on the E-commerce Closed-Loop Supply Chain (E-CLSC) WEEE recycling system, led by remanufacturers, and develops a dual-sided evolutionary game model with remanufacturers and platforms as participants. The model considers the influence of factors such as green innovation, service level, recycling price, and government subsidies. A profit matrix is constructed to analyze the strategic choices of remanufacturers and platforms. Then, this paper conducts a simulation using MATLAB, obtaining data based on the sales and recycling prices of smartphones. Based on evolutionary numerical analysis, the following findings were obtained: (1) Government subsidy policies are formulated based on the required investments for green innovation and service levels, which differ at each stage. (2) The decision of whether remanufacturers engage in green innovation depends largely on the extent to which the technology can reduce remanufacturing costs. They are more inclined to choose green innovation if it can significantly lower costs. (3) Consumer sensitivity to recycling prices also influences the strategic choices of remanufacturers. The more sensitive consumers are to prices, the more waste products remanufacturers can recycle, making green innovation more attractive.

A R T I C L E   I N F O

Keywords:
Recycling;
Waste electrical and electronic equipment (WEEE);
E-commerce;
Closed-loop supply chain;
Green innovation;
Evolutionary game;
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1. Introduction

With the increasing accumulation of waste electrical and electronic equipment (WEEE), the global environment faces significant challenges [1-5]. According to the Global E-Waste Monitor 2020 report [6], a staggering 53.6 million tons of e-waste was generated worldwide in 2019. China alone produced 10.1 million metric tons of WEEE, making it the largest generator of WEEE globally. The hazardous substances found in WEEE pose a significant environmental and public health threat [7-10], while the valuable resources contained within are often underutilized [11, 12]. Consequently, the collection and recycling of WEEE have become a necessity and urgency [13].

Governments worldwide have responded to WEEE with corresponding legislation [14-16]. The Waste Electrical and Electronic Equipment (WEEE) Directive of the European Union [17], Regulations on the Administration of the Recycling and Disposal of Waste Electrical Appliances and Electronic Products, and the Law of the People's Republic of China on the Prevention and Control of Solid Waste Pollution [18] aim to reduce the environmental impact of WEEE by promoting the recovery and reuse of valuable materials from discarded products. Additionally, many socially responsible enterprises have played a critical role in promoting the recycling and reuse of WEEE. For example, Apple has launched the "Apple Reuse and Recycling Program" [19]. Alibaba has launched the "credit recovery" program that encourages consumers to recycle their used products by providing credits redeemable for new products.

Remanufacturing, an effective method of environmental protection, has gained attention from governments and enterprises worldwide. It involves the process of taking end-of-life products and restoring them to their original condition, thereby extending their lifespan and reducing the need for new products [20]. Environmental regulations and growing consumer consciousness have made remanufacturing an indispensable aspect for many manufacturers. Leading companies such as Apple, HP, Sony, Huawei, and Lenovo have started incorporating recycled components into their production processes instead of relying solely on new raw materials. This shift towards remanufacturing is driven not only by environmental concerns but also by the significant cost savings of up to 30-50 % that can be achieved [21].

However, the remanufacturing industry faces many challenges, such as the lack of a quality control system for remanufacturing, insufficient investment in technology research and development, and low rates of remanufacturing for old parts. To support green technology innovation, the U.S. government allocated $2.4 billion to electric vehicle companies [22]. The Chinese government has issued Implementation Plans to further improve the market-oriented green technology innovation system [23]. The rise of third-party online recycling platforms provides new opportunities for the development of reverse supply chains, which allows logistics, information flow, and capital flow to be managed electronically. The development of Internet-based third-party network recycling platforms has created new opportunities for the reverse supply chain, enabling capital flow, information flow, and logistics to be managed electronically. This has led to the formation of an E-commerce closed-loop supply chain (E-CLSC) and provided a new channel for WEEE recycling [24-26].

The recycled WEEE through the E-CLSC is mainly due to product replacement and updates. However, for some consumers (such as mobile phones), these products still have residual and useful value. The platform provides recycling services and has strict recycling testing procedures. After the recycling of WEEE, there are three directions for its reuse: reselling as second-hand products, remanufacturing and dismantling for raw materials.

Despite the scale effect and data advantage of platforms, little attention is paid to WEEE that require remanufacturing and disassembly and processing with lower profits. The available WEEE cannot flow smoothly to the remanufacturer for remanufacturing, resulting in instability for the entire E-CLSC dominated by the remanufacturer. Promoting technological innovation by remanufacturers and encouraging platforms to actively participate in the recycling of WEEE for remanufacturing are therefore crucial. It is worth exploring how to incentivize such innovation to ensure that these stakeholders play a more active role in WEEE recycling and remanufacturing.

The main goal of this article is to construct an evolutionary game model consisting of remanufacturers and platforms to understand in detail the influencing factors and evolution process of the E-CLSC system. Section 2 provides a comprehensive review of the relevant literature. Section 3 presents detailed descriptions of the model, including the assumptions made, and focuses on the construction of the evolutionary game model. Section 4 comprises a thorough numerical analysis. Finally, in Section 5, we conclude our findings.

2. Literature review

The literature review focuses on exploring the existing research on green innovation, government subsidies, and the E-CLSC of recycling. We highlight how our research differs from previous studies and outline the specific contributions our work brings to the field.

2.1 Green innovation and government subsidies

Innovation refereed to changes in design/production/offering of products or services [27], in response to intense competition, companies worldwide have widely recognized technology innovation as an effective measure [28]. Green innovation could benefit remanufacturing because of products becoming more recyclable and easier to remanufacture [29]. In their study, Reimann *et al.* [30] adopted a game-theoretical framework to investigate how remanufacturing is interconnected with the possibility of decreasing variable remanufacturing costs through process innovation. Lee [31] examined a closed-loop supply chain (CLSC) comprising a manufacturer, a retailer, and a collector. The study highlights the necessity for all supply chain members to engage in green innovation initiatives simultaneously in order to attain a mutually beneficial outcome within the CLSC. In order to encourage enterprises to engage in green innovation, governments had adopted subsidies as a means to incentivize innovative behaviors.

In traditional recycling systems, it has been widely acknowledged that government subsidies play a significant role in boosting the participation rate and enhancing the effectiveness of recycling outcomes [32]. The research conducted by Wang *et al.* [33] indicated that the implementation of green insurance subsidies and government subsidies can serve as catalysts for driving innovation within enterprises. He *et al.* [21] examined the optimal channel structure, pricing decisions of manufacturers, and the government's optimal subsidy level across three different channel structures. In a similar vein, Liu *et al.* [34] investigated the impact of government subsidies on the profits of supply chain members. Wan and Hong [35] also showed that government subsidies promote consumption and increase recycling, benefiting the entire recycling chain. According to Aldieri *et al.* [36], the implementation of a green innovation subsidy policy can assist enterprises in adopting green technology and enhancing their employment levels. Huang *et al.* [37] examined the different modes of green credit, manufacturing subsidy, and sales subsidy in a supply chain involving a green manufacturer with limited capital. By conducting a sensitivity analysis on the green degree of recycled products, In the study conducted by Guo *et al.* [38], they provided empirical evidence that supports the adoption of a secondary subsidy strategy by the government for low-green products. This particular strategy was found to serve as an additional incentive for enterprises, effectively encouraging and promoting their endeavors in recycling and remanufacturing. According to Zhou *et al.* [39], the effectiveness of a subsidy greatly depended on its amount. Therefore, in order to ensure successful implementation of policies, the government should establish a scientific and dynamic mechanism for adjusting the subsidy amount. The research of Bai *et al.* [40] aimed to examine the influence of government subsidies on various online channel strategies and how consumer preference for high-quality services factors into this equation. However, existing literature lacks analysis of participants' decision-making processes in an E-CLSC system.

2.2 E-CLSC of recycling

The internet economy has been highly successful in both the forward sales channels and the reverse channels for WEEE [41, 42]. The traditional recycling systems face issues such as a complex chain, ambiguous procedures, and unpredictable costs, but the online recycling industry has made significant progress in addressing these concerns [43].

Various studies have been conducted on the E-CLSC of recycling, focusing on several aspects. Firstly, in terms of recycling channel selection, Feng *et al.* [44] identified four recycling modes and found that the dual-channel approach, combining online and offline channels, outperforms single-channel approaches. Li *et al.* [45] conducted a comparative analysis of online recycling, offline recycling, and mixed recycling models, highlighting the advantages for remanufacturers in online recycling but potential drawbacks for recyclers. Wang *et al.* [46] compared different decisions in the forward and reverse channels, including wholesale vs. direct sales and entrusted recycling vs. direct recycling. Secondly, regarding sales mode selection, Jia and Li [47] proposed that e-retailers should focus on selling new products, while online platforms should prioritize remanufactured products. Zhang and Hou [48] discovered that when online retailers own their brands, the preferred sales mode of manufacturers and e-retailers tends to be opposite, even with asymmetric cost information. Lastly, studies on recycling prices have also been conducted. Matsui [49] examined the timing issue of recycling prices in both online and offline dual channels. The research indicated that offline recycling price should have an advantage over online recycling price at the time of establishment. However, these studies have often neglected the impact of the platform's recycling service level, which plays a significant role in determining the amount of WEEE that can be recycled.

Although extensive research has been conducted on the E-CLSC, there has been limited focus on the dynamic evolution of strategy selection between remanufacturers and platforms in the recycling of WEEE. As a result, we propose the assumption of bounded rationality among remanufacturers and platforms and aim to examine the significant role of government subsidies policy in guiding WEEE recycling practices. This study aims to fill the gap in the existing literature by shedding light on the dynamics of strategy selection and the impact of government interventions in the context of WEEE recycling.

3. Construction of the evolutionary game model

This study investigates a closed-loop e-commerce recycling supply chain, predominantly led by remanufacturers. The remanufacturers collaborate with e-commerce recycling platforms to retrieve discarded products. Consumers, after browsing the recycling information on the platform, provide relevant information about their discarded products. The platform evaluates the value of the discarded products and provides feedback to the consumers. Consumers have the option to either ship the products or opting for doorstep pickup services. The platform delivers the quality-checked waste products to the remanufacturers, who then engage in remanufacturing and sales activities. The remanufacturers reduce remanufacturing costs through green innovations while also minimizing environmental pollution. The E-CLSC structure in which the remanufacturer is dominate of this study is illustrated in Fig. 1.

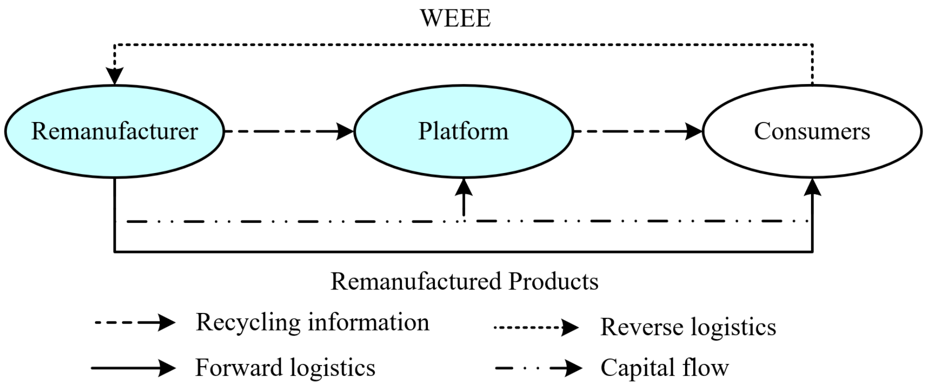


Fig. 1 Structure of E-CLSC model is led by remanufacturer

3.1 Assumptions and notations

To meet the requirements of the evolutionary game theory and our research problems, we make the following assumptions about the model we have constructed in this study. The definitions and explanations of the relevant parameters are presented in Table 1.

Assumption 1. In our model, we incorporate the notion of bounded rationality, assuming that each player has limited rationality. Due to information asymmetry, remanufacturer and platform cannot accurately determine the recycling decisions for WEEE that would maximize their individual interests. Instead, they possess learning and imitating abilities, allowing them to adapt their strategies based on past experiences and observations.

Assumption 2. This paper constructs an evolutionary game model containing two players: remanufacturer and platform. The remanufacturer makes a strategic choice between two options: Green Innovation (GI) and No Green Innovation (NGI), with respective probabilities of x and $1-x$. Similarly, the platform selects between two strategies: Actively Participate (AP) and Inactively Participate (IP), with probabilities of y and $1-y$.

Assumption 3. In the case where the remanufacturer opts for the No Green Innovation (NGI) strategy, we denote the remanufacturing cost as c. However, it is worth noting that green innovation undertaken by the remanufacturer has been shown to effectively decrease the production cost of remanufactured products [29]. The remanufactured cost When the remanufacturer chooses Green Innovation (GI) strategy is $c_1 = (c - re)$, e denotes green innovation effort level, r is the marginal effect of green innovation effort on remanufactured products' production cost. When remanufacturer chooses the GI strategy, an additional cost in green innovation is required. Based on literatures [50-52], the cost can be defined as K = $1/2me^2$. m is the cost sensitivity of green innovation effort level.

Assumption 4. The quantity of WEEE recycled is influenced by the recycling price and the recycling service level. Following the assumptions made by Giovanni and Zaccour [53], we assume that the function describing the recycling quantity q, can be expressed as $q = \beta p_c + \theta s$.

Assumption 5. The higher the level of service provided by a platform, the higher the cost involved. Assuming the platform chooses to actively participate in recycling, the additional cost required is represented by L=$1/2ns^2$ [54]. n is the cost sensitivity of service level.

Table 1 Summary of parameters

Symbol	Description
p	The selling price of the remanufactured product
p_c	The recycling price of a unit of WEEE. Decision variable
μ	The unit commission charged by platform to remanufacturer
r	The marginal effect of green innovation effort on remanufactured cost
c	Unit reproduced costs when green innovations are not implemented
e	The level of green innovation of the remanufacturer, $e > 0$, Exogenous variables
β	Sensitivity of consumer recycling price
θ	Sensitivity of consumer recycling service levels.
s	The level of recycling service
d	The inherent subsidy provided by the government to platforms on a per-unit
f	The inherent subsidy provided by the government to remanufacturer on a per-unit
m	Cost sensitivity of green innovation effort level
n	Cost sensitivity of service level
g	Government subsidies for green innovation in remanufacturers
w	Government subsidies for platforms to improve their service levels
π_{ri}	Profits of remanufacturer
π_{pi}	Profits of platform. $i = 1,2,3,4$: four strategies used by the remanufacturer and the platform

3.2 Model construction

By considering various combinations of strategies between the remanufacturer and the platform, we have determined the benefits matrix, as illustrated in Table 2.

(1) Strategy combination 1: (GI, AP)

In this scenario, remanufacturer chooses to engage in green innovation, while platform opts to actively participate in recycling. The profit functions of the remanufacturer and the platform can be formulated as follows:

$$\pi_{r1} = (p - c_1 - \mu + f - p_c)q - (1 - g)K \tag{1}$$

$$\pi_{p1} = (\mu + d)q - (1 - w)L \tag{2}$$

We thus derive:

$$\begin{cases} p_{c1} = \dfrac{\beta(p - c_1 - \mu + f) - \theta s}{2\beta} \\ q_1 = \dfrac{\beta(p - c_1 - \mu + f) + \theta s}{2} \\ \pi_{r1} = \dfrac{[\beta(p - c_1 - \mu + f) + \theta s]^2}{4\beta} - (1 - g)K \\ \pi_{p1} = (\mu + d)\dfrac{\beta(p - c_1 - \mu + f) + \theta s}{2} - (1 - w)L \end{cases} \tag{3}$$

(2) Strategy combination 2: (GI, IP)

In this scenario, remanufacturer chooses to engage in green innovation, while platform opts to inactively participate in recycling. At this point, the platform does not need to pay more for service levels, for ease of calculation, we let $s = 0, w = 0$. We thus derive:

$$\begin{cases} p_{c2} = \dfrac{p - c_1 - \mu + f}{2} \\ q_2 = \dfrac{\beta(p - c_1 - \mu + f)}{2} \\ \pi_{r2} = \dfrac{\beta(p - c_1 - \mu + f)^2}{4} - (1 - g)K \\ \pi_{p2} = (\mu + d)\dfrac{\beta(p - c_1 - \mu + f)}{2} \end{cases} \tag{4}$$

(3) Strategy combination 3: (NGI, AP)

In this scenario, remanufacturer makes no effort with regard to green innovation, while platform opts to actively participate in recycling. At this point, the remanufacturer does not need to pay more for green innovation, for ease of calculation, let $e = 0$, $g = 0$. We can obtain:

$$\begin{cases} p_{c3} = \dfrac{\beta(p - c - \mu + f) - \theta s}{2\beta} \\ q_3 = \dfrac{\beta(p - c - \mu + f) + \theta s}{2} \\ \pi_{r3} = \dfrac{[\beta(p - c - \mu + f) + \theta s]^2}{4\beta} \\ \pi_{p3} = (\mu + d)\dfrac{\beta(p - c - \mu + f) + \theta s}{2} - (1 - w)L \end{cases} \tag{5}$$

(4) Strategy combination 4: (NGI, IP)

In this scenario, remanufacturer makes no effort with regard to green innovation, and platform opts to inactively participate in recycling. We can get:

$$\begin{cases} p_{c4} = \dfrac{p - c - \mu + f}{2} \\ q_4 = \dfrac{\beta(p - c - \mu + f)}{2} \\ \pi_{r4} = \dfrac{\beta(p - c - \mu + f)^2}{4} \\ \pi_{p4} = (\mu + d)\dfrac{\beta(p - c - \mu + f)}{2} \end{cases} \tag{6}$$

Then, the benefit matrix can be obtained in Table 2.

Table 2 Benefit matrix of remanufacturer and platform

		Platform	
		AP(y)	IP($1-y$)
Remanufacturer	GI(x)	(π_{r1}, π_{p1})	(π_{r2}, π_{p2})
	NGI($1-x$)	(π_{r3}, π_{p3})	(π_{r4}, π_{p4})

Because $q_i > 0, \forall i$, we can obtain $p - c - \mu + f > 0, \pi_{r1} > \pi_{r2}, \pi_{r3} > \pi_{r4}, \pi_{p1} > \pi_{p3}, \pi_{p2} > \pi_{p4}$.

3.3 Evolutionary process

Combined with the benefit matrix in Table 2, the expected benefits for remanufacturer to adopt the GI strategy are

$$U_{11} = y\pi_{r1} + (1-y)\pi_{r2} \tag{7}$$

The expected benefits for remanufacturer to adopt the NGI strategy are

$$U_{12} = y\pi_{r3} + (1-y)\pi_{r4} \tag{8}$$

Average expected benefits of remanufacturer are

$$\overline{U_1} = xU_{11} + (1-x)U_{12} \tag{9}$$

The expected benefits for platform to adopt the AP strategy are

$$U_{21} = x\pi_{p1} + (1-x)\pi_{p3} \tag{10}$$

The expected benefits for platform to adopt the IP strategy are

$$U_{22} = x\pi_{p2} + (1-x)\pi_{p4} \tag{11}$$

Average expected benefits of platform are

$$\overline{U_2} = yU_{21} + (1-y)U_{22} \tag{12}$$

Hence, we can derive the replicated dynamic equations for the remanufacturer and the platform as follows:

$$\begin{cases} F(x) = \dfrac{dx}{dt} = x\left(U_{11} - \overline{U_1}\right) = x(1-x)[y(\pi_{r1} - \pi_{r3}) + (1-y)(\pi_{r2} - \pi_{r4})] \\ H(y) = \dfrac{dy}{dt} = y(U_{21} - \overline{U_2}) = y(1-y)[x(\pi_{p1} - \pi_{p2}) + (1-x)(\pi_{p3} - \pi_{p4})] \end{cases} \tag{13}$$

The dynamic system replication equation (13) describes the evolution of the remanufacturer and e-commerce platform selection strategy system, according to the principle of differential equation stability, when the replication dynamic equation on both sides of the game is equal to zero, the system tends to a steady state. Let $F(x) = 0, H(y) = 0$, because $\pi_{p1} - \pi_{p2} - \pi_{p3} + \pi_{p4} = 0$, we can obtain four evolutionary equilibria (EE), which are (0,0), (0,1), (1,0), (1,1).

3.4 Evolutionary equilibrium stability analysis

Based on the work of Friedman [55], we can determine the stability of equilibrium points by utilizing the Jacobian matrix of the dynamic system. The Jacobian matrix J is as follows:

$$J = \begin{bmatrix} \dfrac{\partial F(x)}{\partial x} & \dfrac{\partial F(x)}{\partial y} \\ \dfrac{\partial H(y)}{\partial x} & \dfrac{\partial H(y)}{\partial y} \end{bmatrix} = \begin{bmatrix} j_{11} & j_{12} \\ j_{21} & j_{22} \end{bmatrix}$$

where,

$$j_{11} = (1-2x)[y(\pi_{r1}-\pi_{r3})+(1-y)(\pi_{r2}-\pi_{r4})]$$
$$j_{12} = x(1-x)(\pi_{r1}-\pi_{r3}-\pi_{r2}+\pi_{r4})$$
$$j_{21} = y(1-y)\left(\pi_{p1}-\pi_{p2}-\pi_{p3}+\pi_{p4}\right)$$
$$j_{22} = (1-2y)[x(\pi_{p1}-\pi_{p2})+(1-x)(\pi_{p3}-\pi_{p4})]$$

To evaluate the stability of each equilibrium point, we can calculate the determinant and trace of matrix J. The stability of an equilibrium point is determined based on the signs of its determinant and trace. In particular, if the determinant is positive and the trace is negative, the equilibrium point demonstrates local stability. This signifies that the equilibrium point represents an evolutionary stable strategy (ESS).

According to the method of local stability analysis of Jacobian matrix, stability analysis was performed on four equilibrium points. Through calculation, the $\det J$ and trJ corresponding to the four replication dynamic equilibrium points can be obtained, and the local asymptotic stability analysis results are obtained according to the results of $\det J$ and trJ, the replication dynamic mechanism to find the system evolution stability strategy conditions, as depicted in Table 3.

Table 3 $\det J$ and trJ of four equilibrium points

EE	$\det J$	trJ
(1,1)	$(\pi_{r1}-\pi_{r3})(\pi_{p1}-\pi_{p2})$	$-(\pi_{r1}-\pi_{r3})-(\pi_{p1}-\pi_{p2})$
(1,0)	$-(\pi_{r2}-\pi_{r4})(\pi_{p3}-\pi_{p4})$	$-(\pi_{r2}-\pi_{r4})+(\pi_{p3}-\pi_{p4})$
(0,1)	$-(\pi_{r1}-\pi_{r3})(\pi_{p3}-\pi_{p4})$	$(\pi_{r1}-\pi_{r3})-(\pi_{p3}-\pi_{p4})$
(0,0)	$(\pi_{r2}-\pi_{r4})(\pi_{p3}-\pi_{p4})$	$(\pi_{r2}-\pi_{r4})+(\pi_{p3}-\pi_{p4})$

For equilibrium points where the determinant ($\det J$) of the Jacobian matrix is greater than 0 and the trace (trJ) is less than 0, we classify them as partial equilibrium stability points. Due to the constraints of length, it is unnecessary to analyze all Evolutionary Stable Strategies (ESSs). In the context of this study on the manufacturer-led E-CLSC system, our main focus is on how to promote green innovation in remanufacturing and encourage e-commerce platforms to actively participate in WEEE recycling through government subsidies. In other words, our focus is on how to adjust subsidy policies in order to encourage remanufacturers and platforms to lean towards choosing the combined strategy (GI, AP). Therefore, we will focus on discussing how to make the stable points of the system tend towards (1,1).

When (1,1) is the partial equilibrium stability point, we can obtain that $(\pi_{r1}-\pi_{r3})(\pi_{p1}-\pi_{p2})>0$ and $-(\pi_{r1}-\pi_{r3})-(\pi_{p1}-\pi_{p2})<0$. According to the two conditions, we can derive that $\pi_{r1}-\pi_{r3}>0$ and $\pi_{p1}-\pi_{p2}>0$.

Combined with Equations (1)-(6), it is obtained

$$\begin{cases} f > \dfrac{2me(1-g)-2r\theta s-\beta r^2 e-2\beta r(p-c-\mu)}{2\beta r} \\ d > \dfrac{ns(1-w)-\theta\mu}{\theta} \end{cases} \tag{14}$$

4. Simulation

In this section, we utilize MATLAB R2016a software to perform a numerical study that aims to validate the evolutionary game model and investigate the modifications in the behavioral strategies of the remanufacturer and the platform through sensitivity analysis of the model parameters. The parameter values used in the study are predominantly based on the sales price of Huawei smartphones in China in 2021. It is noted that Huawei sold smartphones at an average price of 4 thousand yuan per unit during that year. The manufacturing cost accounts for approximately 50 %, which is around 2 thousand yuan/unit. We assume the commission paid to platform is 0.1 per unit, and the green innovation effort level and service effort level are both 0.1. According to the "Several Measures of Beijing Municipality on Further Improving the Market-oriented Green Technology Innovation System" issued by the Beijing Municipal Development and Reform Commission, the proportion of government subsidies for enterprise technological innovation generally does not exceed 30 % of the total investment [56], i.e. $g = 0.3$, $w = 0.3$.

(1) The influence of green innovation on cost sensitivity

Through the above analysis, the parameters in this situation are set as follows: $p = 4$, $c = 2$, $\mu = 0.5$, $e = 0.1$, $s = 0.1$, $r = 10$, $\beta = 0.8$, $\theta = 0.8$, $f = 0.5$, $n = 8$, $g = 0.3$, $w = 0.3$, $d = 0.1$. From Fig. 2, we can see that the choice of green innovation by remanufacturers varies with changes in the investment cost of green innovation. According to the theory of industrial life cycle [57], China's WEEE recycling industry can be classified into three distinct stages: the initial stage, intermediate stage, and mature stage. Each stage represents a different phase of development and progress in the WEEE recycling industry in China [18]. Similarly, the development of green innovation for remanufacturers can also be divided into three stages. In the early stage of green innovation, technology is in its infancy and requires significant investment in laboratory construction and recruitment of personnel. The level of investment required to improve the unit's green innovation efforts is substantial, denoted as $m = 300$ million. In the intermediate stage of green innovation, where the initial infrastructure is already established ($m = 200$ million), and in the mature stage of green technological innovation, where the innovation foundation and environment are well-developed ($m =$100 million), the required investment for green technology innovation decreases. Fig. 2 illustrates that the government's subsidy ratio for green innovation by remanufacturers remains consistent at 0.5 across these three stages. However, the choices made by remanufacturers differ, reflecting the current attitude of Chinese enterprises towards green technology innovation. It is observed that most companies tend to adopt green innovation technologies into product production when they have already gained market presence and reached a mature stage.

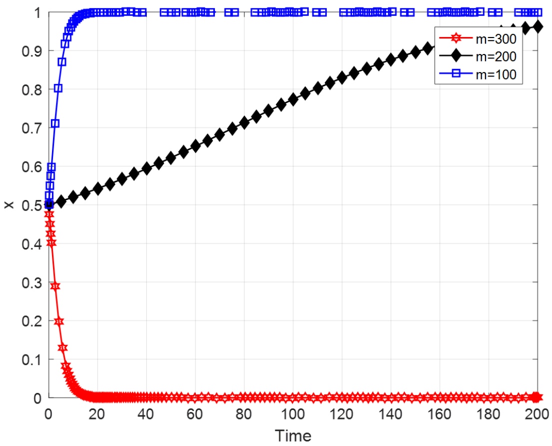


Fig. 2 The influence of green innovation on cost sensitivity

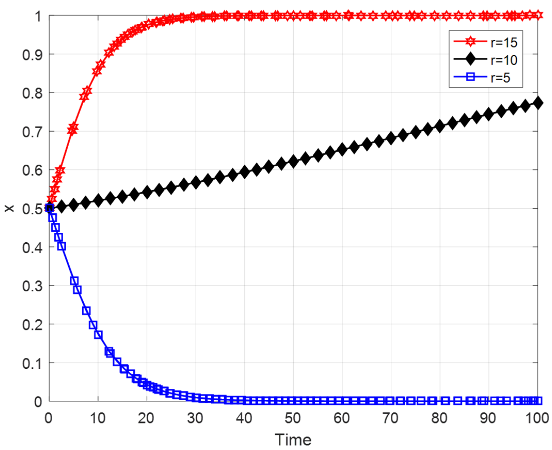


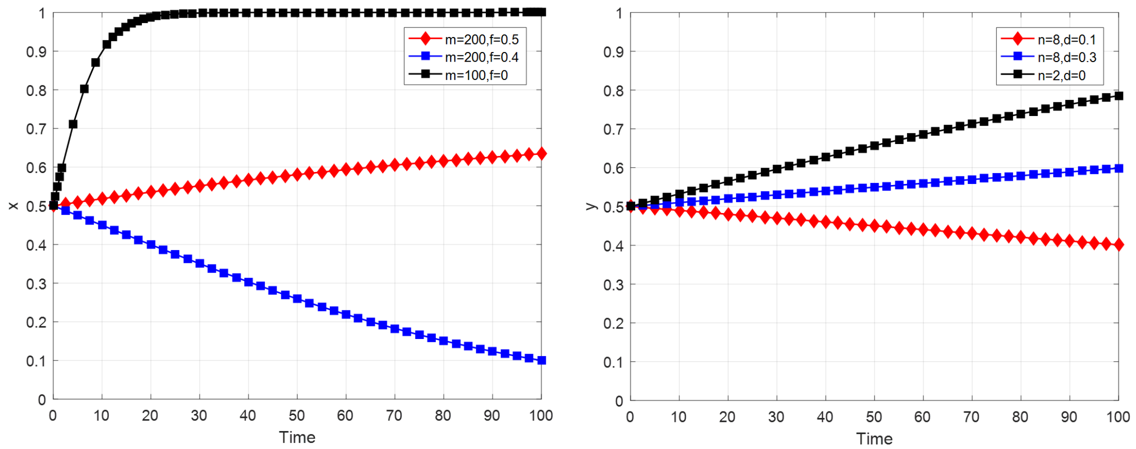
Fig. 3 Green innovation on remanufactured cost sensitivity

(2) The influence of green innovation on remanufactured cost sensitivity

Keeping other parameters unchanged, let's consider the case where $m = 200$ and examine the impact of the degree of cost reduction resulting from green innovation on the decision-making of remanufacturers. By setting r to values of 5, 10, and 15, we can observe Fig. 3. In this scenario, remanufacturers evaluate the adoption of green innovation based on its potential to reduce production costs per unit. With a fixed coefficient for the cost of investing in green innovation, they assess whether the implementation of green innovation can effectively lower their overall remanufactured costs. The higher the cost reduction achieved per unit of green innovation effort, the more likely remanufacturers are to choose green innovation.

(3) The influence of government subsidies

Keeping other parameters unchanged, let $m = 200$ and substitute the respective parameters into equation (14). We can calculate that when $f > 0.4$ and $d > 0.2$, which means the government provides a production subsidy of 0.4 units for each green innovation product, and the platform also receives a recycling subsidy of 0.2 units for each product recycled, the system's stable point will tend toward (1, 1). As shown in Fig. 4(a), during the intermediate stage of technological innovation, when f takes a value of 0.4, over time, remanufacturers will ultimately lean towards choosing NGI (Non-Green Innovation). However, when f takes a value of 0.5, although the curve is relatively flat, with the passage of time, remanufacturers will still choose GI (Green Innovation) after a longer period. Once a technology enters the mature stage ($m = 100$), where the required cost for each unit of green innovation significantly decreases, as depicted in Fig. 4(a), even if the government no longer provides production subsidies, the remanufacturers' GI selection curve will quickly converge to 1.



(a) Remanufacturer (b) Platform

Fig. 4 The influence of government subsidies on remanufacturer and platform selection

Similarly, for the platform, as shown in Fig. 4(b), during the initial stage of product recycling, there is a need for increased investment to enhance the service level ($n = 8$). When d takes a value of 0.1, over time, the platform will ultimately lean towards choosing the IP (Inactively Participate) strategy. However, when d takes a value of 0.3, after a longer period, the platform will eventually choose the AP (Actively Participate) strategy. Once the platform's recycling approach becomes well-established among consumers, reaching the mature stage of platform recycling ($n = 2$), the platform no longer requires substantial investment to attract consumers to choose the e-commerce platform for recycling. At this stage, even if the government no longer provides recycling subsidies ($d = 0$), the platform will actively participate in the platform recycling model.

Similarly to the previous discussion, we can also discuss the government's subsidies for technological innovation and platform services. As shown in the Fig. 5, during the early to mid-term of technological investment ($m = 200$), when $g = 0.3$, remanufacturers will choose the GI strategy. However, if the government reduces subsidies for technological investment, i.e., $g = 0.2$, remanufacturers will opt for the NGI strategy. As technology continues to mature ($m =$

150), despite the decrease in technological investment subsidies ($g = 0.2$), remanufacturers will still choose the GI strategy. The same logic applies to the platform's strategy selection.

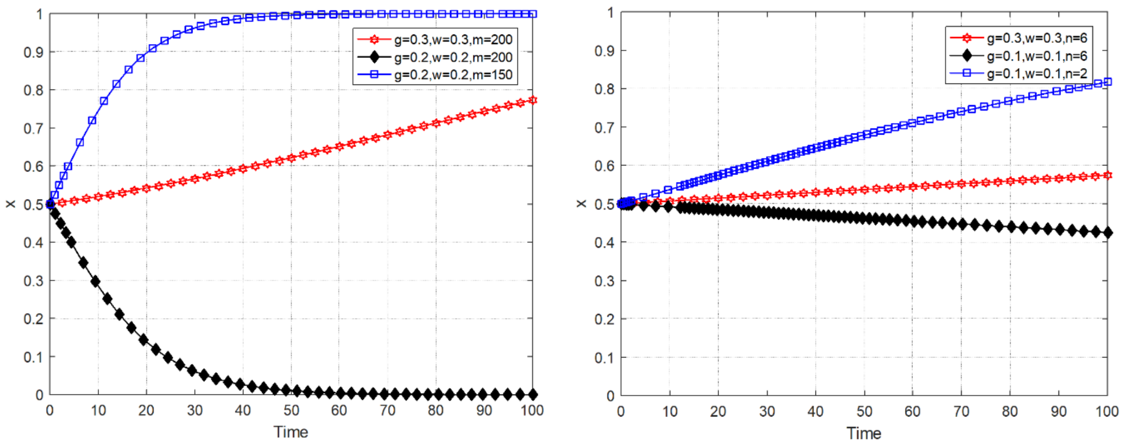


Fig. 5 The influence of government technology subsidy ratio

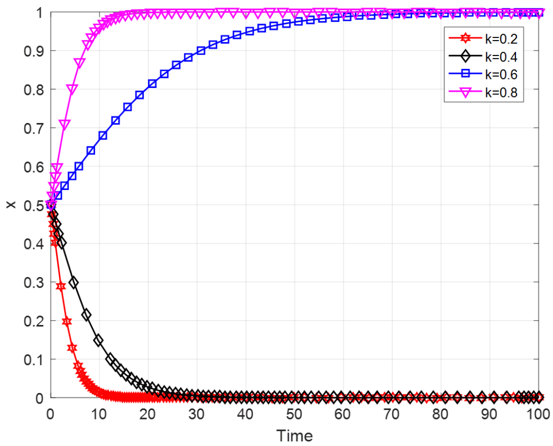


Fig. 6 The influence of recycling price coefficient

(4) The influence of recycling price coefficient

Keeping other parameters unchanged, let $m = 200, n = 8, r = 10, f = 0.5$. By setting different values for k, namely 0.2, 0.4, 0.6, and 0.8, we can obtain Fig. 6. From Fig. 5, it can be observed that the recycling price coefficient significantly influences the decisions of remanufacturers. As the value of k increases, the remanufacturers' choices shift from NGI to GI. Moreover, as the value of k becomes larger, the probability curve of remanufacturers choosing the GI strategy converges at a faster rate.

5. Conclusion

This study focuses on the research of the E-CLSC WEEE recycling system, with remanufacturers as the main actors. This study adopts an evolutionary game approach to analyze the decision-making processes of remanufacturers with regards to green innovation and the platform's selection of actively participating in recycling. By employing evolutionary stability strategies and stable conditions, we derive the profit matrix and evolution path for both sides. Furthermore, we provide a concise and detailed analysis of how the main parameters affect these decisions. Overall, this research sheds light on the dynamics of decision-making in the context of green innovation and active recycling within an evolutionary game framework. In the model developed in this study, we consider the impact of green innovation on remanufactured costs. This allows us to analyze how the adoption of green innovation affects the overall costs involved in the remanufacturing process. Additionally, the remanufacturers' fixed capital investment in green innovation is considered. Furthermore, based on the practical application of recycling on e-commerce platforms, the price of recycling and the platform's service level are factors that affect the quantity of recycling. This study introduces a functional relationship between the quantity of recycling, price, and service level. Building upon these conditions, the study further investigates how government subsidies will impact the strategic choices of both decision-making parties. Based on the findings of the research analysis, the following management suggestions are derived:

- Both the development of green innovation and platform recycling models can be categorized into three distinct stages. In the initial stage, significant capital investment is required for the development of both green innovation and platform recycling models. During this stage, the government needs to provide substantial subsidies to remanufacturers for unit product remanufacturing and green innovation investments. Only then will remanufacturers choose to adopt green innovation (GI). Similarly, in the initial stage of the platform recycling model, the platform needs to invest a considerable amount of funds in promotion, channel development, etc. Without sufficient government subsidies, the platform is often reluctant to actively participate (AP) in recycling. However, in the mature stage, green innovation has already established a certain technological foundation, and the required investments in green innovation and platform services have significantly decreased. During this stage, even without government subsidies, remanufacturers will choose green innovation (GI), and the platform will actively engage in recycling. Therefore, when formulating green innovation subsidy policies, the government needs to consider the current innovation environment, innovation foundation, and adjust subsidy policies accordingly during different stages of development.
- The degree to which green innovation technology reduces remanufacturing costs is a crucial factor in the decision-making process of remanufacturers regarding whether to adopt green innovation. If the green innovation technology offers only minimal reduction in remanufacturing costs, regardless of the amount of investment required, remanufacturers will not choose the green innovation strategy.
- The sensitivity of consumers to recycling prices has a significant impact on the strategy choices of remanufacturers in an E-CLSC system. When consumers have a low sensitivity to recycling prices, a majority of them may choose to discard or keep their used products rather than sell them to the platform. As a consequence, this could lead to a relatively low volume of waste products being recycled within the system, which in turn may limit the profitability of remanufacturers from reselling these products. In this situation, remanufacturers are unlikely to choose green innovation. However, when consumers have a higher sensitivity to recycling prices, it indicates that they are attracted by the prices offered for their used products and are willing to sell them. This results in a larger quantity of waste products being collected by remanufacturers, who can then profit from selling them after undergoing remanufacturing. In this scenario, remanufacturers are more likely to choose green innovation.
- The model proposed in this paper can be applied to various scenarios in different countries and regions. However, the levels of government subsidies, technological development, product sales prices, and recycling prices may vary among different countries and regions. Therefore, the analysis results will also vary with changes in these parameters.
- It is important to acknowledge certain limitations in our study. Firstly, we did not consider the influence and role of other stakeholders within the closed-loop supply chain on the governance mechanism. For instance, consumer environmental awareness can greatly influence the amount of WEEE recycled, thereby influencing the strategies pursued by remanufacturers. Secondly, this paper focused solely on government subsidies as a variable to examine the decision-making mechanism of remanufacturers and platforms, without considering the government as an active participant in the system. Thirdly, we did

not consider the impact of development level on the government subsidy intensity. Therefore, future research should aim to develop new approaches that encompass the remanufacturer, platform, and consumer within a comprehensive framework.

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