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Analysis of Evolution Mechanism and Optimal Reward-Penalty Mechanism for Collection Strategies in Reverse Supply Chains: The Case of Waste Mobile Phones in China

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Abstract: The aim of this paper is to discuss the coopetition (cooperative competition) relationship between a manufacturer and a collector in the collection of waste mobile phones (WMPs) and examine the evolution mechanism and the internal reward-penalty mechanism (RPM) for their collection strategies. A coopetition evolutionary game model based on evolutionary game theory was developed to obtain their common and evolutional collection strategies. The pure-strategy Nash equilibriums of this model were obtained which showed their collection strategy choices of perfect competition or cooperation. The mixed strategy Nash equilibrium was obtained which revealed evolution trends and laws. In addition, the optimal RPM was obtained in the sensitivity analysis of related parameters. The example of WMPs in China was taken to examine the simulation of the RPM. Results show that (i) although the manufacturer and the collector may change their strategies of cooperation and competition over time, cooperation is their best choice to increase payoffs; (ii) the optimal RPM is beneficial to propel their cooperation tendency and then to increase their payoffs.

Keywords: reverse supply chain; collection strategy; waste mobile phones; evolutionary game theory; evolution mechanism; reward-penalty mechanism

1. Introduction

Mobile phones have become essential parts of daily life and the most commonly manufactured electronic equipment [1]. Since China became the largest producer and seller of mobile phones in 2004, the total number of mobile phone users has achieved 1.5 billion in 2018 [2]. The life expectancy of a mobile phone is shorter than 3 years according to studies from many scholars [3–5]. Obviously, the generation of waste mobile phones (WMPs) is huge and now they have become an environmental problem as a part of waste electrical and electronic equipment (WEEE). In 2017, there were approximately 1 billion WMPs in China, and the recycling rate was only 2% [6]. However, WEEE management has been implemented in developed countries since 2000 [7–9], and many compulsory laws and directives such as the EU Directive on WEEE (2002/96/EC) [10], its revised version (2008/34/EC) [11], and the newest one (2012/19/EU) [12] have been enacted based on extended producer responsibility (EPR) principles. The Directive (2012/19/EU) requires that 75% of WMPs should be recovered, and 55% of WMPs should be reused and recycled by 2018 [12]. The EPR principles require producers including manufacturers and importers to take responsibility for the whole lifespan of a product, especially for the collecting, dismantling, and recycling at its end-of-life stage [13].

The collection of WMPs in the reverse supply chain (RSC) is mainly conducted by formal collectors in many developed countries. Switzerland first established a formal and comprehensive management system of WEEE, which is well operated with producer responsibility organizations (PROs) [14]. Manufacturers, importers, distributors, and retailers collect WMPs through established collection points and retail locations supported by the Swiss Association for Information, Communication and Organization Technology, which is one of the most important PROs [15]. In Japan, the *Law on the Promotion of Recycling and Reuse of Used Small Electronic Equipment* was enacted to support the tack-back of 28 types of small electronic products including WMPs in 2012 [16]. Under the guidance of related laws, retailers and mobile phone operators have collected WMPs through recycling bins at their business outlets [17].

In many developing countries including China, the collection of WMPs is conducted by formal and informal collectors [18–20]. Street peddlers and repairers in China dismantle WMPs harmfully and crudely and put them into the market with rough refurbishment, who are the leading collectors in the informal collection. As to the formal collection, there are mainly two ways in China. One is the manufacturer's collection, such as the Old-for-New (OFN) service of Mi (http://huanxin.mi.com), and the other is the collector's collection like the third-party collection platform represented by Aihuishou (https://www.aihuishou.com/shouji). They have a competitive and cooperative relationship for WMPs collection. The collector can be served for the manufacturer. On the other hand, they also compete for the surplus value of WMPs such as remanufacturing materials. One of main reasons why they engage in e-waste collection is to recapture the value of the recycled materials and end-of-life products [21]. Their coopetition (cooperative competition) relationship continues throughout the whole game process, and they adjust with each other's strategy according to opponent's responses and their own payoffs.

The relationship between the manufacturer and the collector can be presented by evolutionary game theory (EGT) which assumes the man of bounded rationality [22]. It is more in line with the reality because of incomplete information and changing environment. The EGT emphasizes the behavioral interaction among players which can affect their payoffs directly. The behavioral interaction between the manufacturer and the collector in the WMPs collection is who will do the collection and how to bind them with a contract. They develop their own strategies in the process of the interaction. The EGT can entirely reflect the relationship between strategies change and payoffs fluctuation, can also effectively reflect their complex coopetition relationships. Rosas [23] pointed out that social scientists usually exploit the EGT to study human cooperation. Ji et al. [24] argued that the EGT can effectively observe the changing of cooperation tendency among multi-stakeholders. Some studies have exploited the EGT to analyze the collection of WEEE. Esmaeili et al. [25] adapted the EGT to discuss whether performing collection or not for the manufacturer and the retailer. Wu and Xiong [26] studied cooperation behavior between manufacturers and collectors under a government subsidy mechanism with the EGT.

Except for the subsidy mechanism, the reward-penalty mechanism (RPM) made by the government in a closed-loop supply chain is examined by Wang et al. [27–30]. The RPM is one of incentive mechanisms which are usually used to coordinate forward and reverse supply chains. The producers will face penalties if they cannot achieve the target collection rate set by the EU Directives on WEEE. Unlike this, the Chinese government prefers subsidies or rewards, which set up a WEEE treatment fund in 2012 [31] and added the WMPs to the *Waste Electrical and Electronic Equipment Treatment Directory (2014 Edition)* in 2015 [32]. The EPR principles were adopted in this fund. Specifically, the government levies funds on the electrical and electronic equipment producers and provides subsidies or rewards to authorized WEEE dismantling companies according to their actual disposal quantity. The RPM for the manufacturer and the collector is conducive to enhancing collection rate and increasing their payoffs. In addition, the RPM can be used to promote positive strategy evolution. Therefore, we examine an internal RPM negotiated by the manufacturer and the collector, which is rare in other literature.

Based on the theory and practice of the RSC, EGT, RPM, and the motivating example, we investigate an RSC comprising one manufacturer and one collector under an RPM. This paper uses the evolutionary game to discuss the relationships between members in the RSC and to analyze the evolution mechanism of their collection strategies, meanwhile, an optimal RPM is obtained. Finally, we take the collection of Chinese WMPs as an example to conduct the simulation of the RPM. Specifically, we address the following research questions:

(1) What kind of relationship between the manufacturer and the collector is beneficial to them?
(2) How does the evolution mechanism of their collection strategies affect their coopetition?
(3) What kind of RPM should be negotiated by them?

This paper exploits the EGT to discuss the coopetition relationship between a manufacturer and a collector in the collection and to examine the evolution mechanism and the optimal RPM for their collection strategies. Their strategy changes, evolution trends, and payoff fluctuations have been thoroughly studied, which is rare in other literature. The majority of incentive mechanisms is imposed by the government in a closed-loop supply chain (CLSC); there are few internal RPMs from players. However, this paper provides the internal RPM negotiated by the manufacturer and the collector.

The remainder of this paper is organized as follows. In the next section, we provide a literature review. The coopetition evolutionary game model (CEGM) is given in Section 3. Section 4 provides the analysis of evolutionary stability strategy (ESS) and the detailed analysis of the model including the optimal RPM. The simulation of the RPM is conducted in Section 5. Section 6 concludes this paper, discusses managerial implications, and proposes future research opportunities. List of acronyms in this paper is shown in Appendix A.

2. Literature Review

The RSC contains activities of product acquisition, reverse logistics, testing, sorting, refurbishing, and remarketing [33]. A great deal of work has been done in the WEEE collection, as reviewed in Section 2.1. In Section 2.2, we discuss incentive mechanisms for an RSC. The applications of the EGT are reviewed in Section 2.3.

2.1. WEEE Collection

WEEE management has attracted many scholars' interests all over the world. Hischier et al. [34] investigated the positive impacts on the environment of the Swiss take-back and recycling systems for WEEE. Ylä-Mella et al. [35] described the implementation of the WEEE Directive and the development of the WEEE recovery infrastructure in Finland and found that they have made a success. Chi et al. [4] found that informal collection was the primary disposal channel of urban household e-waste after they investigated the collection channels of e-waste and household recycling behaviors in Taizhou, China. Jang [36] presented an overview of recycling practices and the management of WEEE since the EPR policy was introduced in South Korea in 2003. Pathak et al. [37] pointed out that although the Indian legislation has been improved and the EPR principles have been implemented, the grey market for WEEE has been enlarged by the social-economic structures of India with a large population of lower-to-middle income groups.

WEEE collection is the first and crucial step in an RSC of WEEE. In Europe, the majority of collection schemes for WEEE has been established in partnership with existing municipal collection schemes for recyclables and hazardous household waste, and additional take-back schemes by retailers [38]. In Canada, Recycle My Cell is a national WMPs recycling program which operates more than 3500 drop-off locations in the country. Besides, Customers can return their used mobile devices with a postage-paid service [39]. Similar to Canada, Australia also has over 3500 WMPs drop-off points and provides pre-paid shipping service to return [39]. In Japan, though, consumers must pay the end-of-life fees that cover part of the recycling and transportation costs while manufacturers afford the rest of the cost [40]. Completely different from the above developed countries, the manufacturer, the retailer, and the collector need to buy back WEEE from consumers in China. HUAWEI, one of mobile phone manufacturing giants in China, initiated an online recycling program called "Green Action 2.0" to carry out the OFN policy which provided up to 798 USD cash coupon for new purchase [41]. Large online retailers such as Jingdong and Suning set up OFN websites to collect the WEEE including WMPs. The third-party collection platform represented by Aihuishou also has the online collection system, and it has established four collection modes of store collection, face-to-face collection, mailing collection, and collecting machine collection [42].

There are formal and informal collection channels in many developing countries. Nduneseokwu et al. [43] examined factors influencing consumers' intentions to participate in a formal e-waste collection system in Nigeria, suggested enhancing consumer's intentions to choose the formal collection and developing an e-waste collection infrastructure. Wang et al. [44] investigated barriers to the formal collection of e-waste in China which mainly were households' preference and informal collectors. Chi et al. [4] pointed out that economic benefit and convenience of disposal were the key factors of choosing collection channels for customers in China, and informal collectors had these advantages. Pathak et al. [37] argued that the informal collection and treatment of WEEE in India have become a serious threat to the sustainable development of the country. Li et al. [45] presented governance mechanisms out of governments and enterprises to control informal collection. There are the monopolistic and competitive take-back schemes for WEEE recycling between competing manufacturers and recyclers in Europe. Toyasaki et al. [46] found that the competitive recycling channel usually achieves a win–win situation. In addition to these kinds of collection channels, there are other channels decided by structure power, such as a manufacturer-led collection channel, a retailer-led collection channel, and a third-party collector-led collection channel [47–49].

This paper focuses on the formal collection system of WMPs in China, discusses the coopetition relationship between the manufacturer and the collector and their collection strategies. Different from most of the existing literature, we investigate their parallel relationship in the RSC.

2.2. Incentive Mechanisms for RSCs

Most of incentive mechanisms are set by the government. One of them is government subsidy, several researchers have reviewed the positive effects of subsidies on the WEEE collection especially on the formal one and environment in China [50–52]. In June 2009, the Chinese government introduced the OFN policy which stipulated that consumers trading in WEEE for new goods could get subsidy up to 10% of the price of the new products [53]. Besides, authorized WEEE recycling enterprises can receive subsidies for WEEE treatment provided by the government, which has continued to the present. This policy has greatly promoted the development of the formal WEEE treatment in China. However, this policy towards consumers expired at the end of 2011 for short of financial support. To better implement the EPR principles and maintain the policy sustainability, Gu et al. [54] redesigned the WEEE fund mode in China. Liu et al. [55] agreed that the government subsidy is beneficial to the development of the formal sector, but the marginal effect of that is not strong when at a higher quality level of e-waste. In addition to subsides, the RPM from the government has been examined. Wang et al. investigated some RPMs under the centralized, the manufacturer-led, and the collector-led CLSCs [28]. Wang et al. also examined the CLSC consisting of two sequential competing manufacturers and one retailer with or without the RPM from the government [29].

To the best of our knowledge, few studies discussed incentive mechanisms from members in the RSC, except for Jørgensen et al. [56] and De Giovanni [57], who have examined the endogenous incentive mechanisms, but their setting was the manufacturer as the leader and the retailer as the follower. The most similar setting with this paper is De Giovanni et al. [58], who discussed a two-sided incentive problem in a dynamic CLSC made up of a manufacturer and a retailer to increase the return rate of end-of-use products, and the manufacturer and the retailer carried out the incentive strategies jointly. Different from above literature, our study is focusing on the two-sided internal incentive mechanism negotiated by the manufacturer and the collector and implemented by the manufacturer. The motivation of the mechanism is to coordinate their strategies and to maximize their payoffs.

2.3. Applications of the EGT

The EGT has been used to deal with cooperation and competition relationships between two parties and to observe their evolution trends. Feng et al. [59] applied the EGT to analyze cooperation and competition behavior of partners in the supply chain of prefabricated construction. Cheng et al. [60] discussed the technology-licensing cooperation problem of two firms with the EGT and obtained the evolution trend of the technology-licensing deal and cooperation strategy under the fixed-fee licensing and royalty licensing situation. An evolutionary game model was built by Yuan et al. [61] to analyze the evolution process of long-term cooperation between the manufacturer's emission reduction and the retailer's low-carbon promotion. Ji et al. [24] developed an evolutionary game model to analyze their long-term green purchasing relationships between suppliers and manufacturers and to observe their cooperation tendency. The EGT takes the frequencies of strategies adopted during the evolutionary game process as the evaluation criterion for decision-making. Then the replicator dynamic method [62], the simulation method [63], and the differential equation method [64] were proposed to solve the frequencies and the game equilibrium.

There were many scholars studying the RSCs with EGT. Wang et al. [65] examined whether two manufacturers took an active part in recycling in the RSC with the EGT. Fu et al. [66] studied the recycling channel decision under competition between two RSCs consisting of one recycler and one waste handler respectively based on the evolutionary game. Han and Xue [67] also used the EGT to study the recycling channel decision with two competitive manufactures and one dominant retailer. The EGT was adopted by Tomita and Kusukawa [68] to analyze the evolutionary stability for behavior strategies of the retailer's cooperation and the manufacturer's monitoring in the RSC. In this paper, we also adopt the EGT to examine the collection strategies in the RSC. However, we extend the prior studies to investigate the coopetition relationship between the manufacturer and the collector in the RSC under the RPM, which is one focus of this paper. Their collection strategies and evolution trends, and the optimal RPM are derived by using the replicator dynamics.

3. Coopetition Evolutionary Game Model

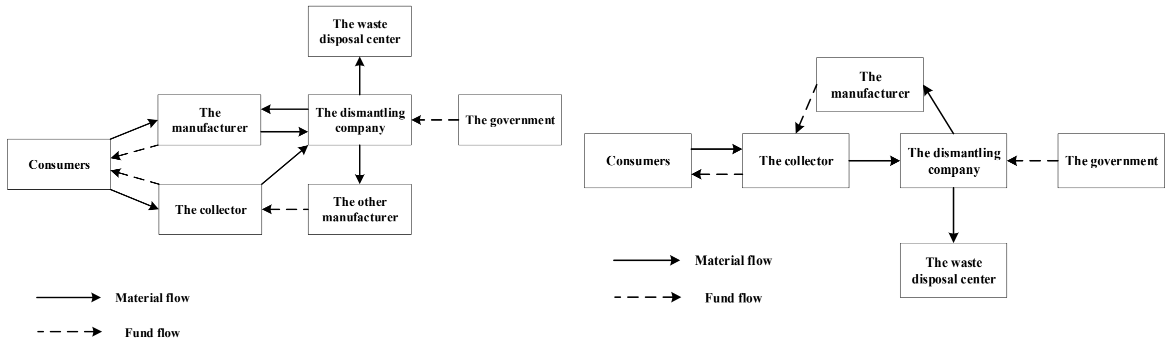
3.1. Problem Definition

The manufacturer such as Mi can collect waste phones by himself and can also authorize the third-party collector such as Aihuishou to undertake the collecting tasks. This paper will refer to the manufacturer as "he" and to the third-party collector as "she" hereinafter. Their choices of strategy are presented in Table 1. When he chooses the competitive strategy, he will undertake the task of self-collection, i.e., take into account both manufacturing and collecting; When he chooses the cooperation strategy, he will authorize her to undertake the collection, but there may be some risks of cooperation such as uncontrollable collecting process and difficult to guarantee service quality. When she chooses the competitive strategy, she will collect his waste phones for other manufacturers, which will reduce his remanufacturing materials; Otherwise, she will collect the waste phones for him.

Table 1. Their strategy choices.

	Competitive Strategy	**Cooperation Strategy**
Manufacturer	Self-collection	Authorizing the collector to undertake collection
Collector	Collecting his waste phones for other manufacturers	Collecting waste phones for him

There are several parties including the manufactures, the collector, the dismantling company, the waste disposal center, the government, and consumers to achieve the collection in the RSC. Consumers' waste phones would be bought back by the manufacturer and the collector for collection, then the waste ones would be disassembled by the dismantling company. The company will deliver remanufacturing materials to the corresponding manufacturer according to the collecting source of the waste phones, namely, returning them to him who takes the self-collection or to the manufacturer who cooperates with her. Here we assume that the other manufacturer does not take the collection. The government funds the dismantling company for environmental protection and resources conservation, and the cooperative manufacturer pays the collector collecting fees. The RSC structure in the competitive and cooperation situation is shown in Figure 1.



(**a**) In the competitive situation (**b**) In the cooperation situation

Figure 1. RSC structure in the competitive and cooperation situation.

As shown in Figure 1, they compete for the collection of consumers' WMPs in the competitive situation, and she collects his WMPs for the other manufacturer. Then the dismantling company delivers remanufacturing materials to the manufacturers according to the source of the waste. While in the case of cooperation, all the waste ones are collected by her for him. Then the dismantling company only delivers the remanufacturing materials to him. The key point of this RSC structure lies in their choice of collection strategies. Thus, we study the RSC consisting of one manufacturer and one collector.

3.2. Notations and Assumptions

The following notations in Table 2 are used throughout the paper:

Table 2. Notations.

Symbol	Description
Parameters	
v_s	His basic income from manufacturing
e_s	Operating cost of his self-collection including fees of buy-back and transportation
c_s	Risk cost of his choice of cooperation caused by her not achieving the excepted quantity and quality of collected products
v_t	Her basic income from collecting WMPs for other manufacturers
c_t	Initial cost of her choice of cooperation for additional service personnel and facilities
e_t	Operating cost of her collection including fees of buy-back and transportation
l	Reward implemented by him for her successful service
k	Penalty implemented by him for her failed service, which means that she does not meet his requirements for the quantity and quality of the collection
β	Probability of her service failure which depends on the random quantity and quality of WMPs, $0 < \beta < 1$
Δv_s	His potential profit from additional remanufacturing materials in a cooperative strategy
Δv_t	Her potential profit from additional collecting income in a cooperative strategy
Variables	
p	Probability of his choice of cooperation
q	Probability of her choice of cooperation

The following assumptions are made in the light of the actual situation and the characteristics of the model.

(1) The total amount and quality of collected phones would not be changed by their different strategies.
(2) His basic income is greater than the sum of the operating cost of his self-collection and the risk cost of his cooperation, namely, $v_s > e_s + c_s$; Her basic income is greater than the initial cost of her cooperation, that is, $v_t > c_t$.
(3) To ensure that the both sides have the potential to cooperate, their potential profits are higher than cooperative risk inputs, namely, $\Delta v_s > c_s + l$, $\Delta v_t > e_t + c_t + k$.

3.3. Modeling

To improve their cooperative quality and protect their interests, this paper introduced an RPM (l, k) under cooperation, which is negotiated by them and implemented by him. Their payoff matrix of the CEGM is set up based on the model descriptions and assumptions above, as shown in Table 3.

Table 3. Payoff matrix of the CEGM.

Manufacturer \ Collector	Competition $(1-q)$	Cooperation (q)
Competition $(1-p)$	$v_s - e_s, v_t$	$v_s - e_s, v_t - c_t$
Cooperation (p)	$v_s - e_s - c_s, v_t$	$v_s - (1-\beta)l + \beta k - c_s + \Delta v_s,$ $v_t + (1-\beta)l - \beta k - e_t - c_t + \Delta v_t$

As can be seen in Table 3, when they both adopt the competitive strategy, his income is the basic income excluding the operating cost of self-collection, namely $v_s - e_s$, and her income is the basic income v_t; When he takes the competition strategy and she takes the opposite one, his income is still $v_s - e_s$, but her income is the basic income excluding the initial cost of choosing cooperation, i.e., $v_t - c_t$. In addition, when he adopts the cooperation strategy and she is the opposite, his income is the basic income excluding the sum of the operating cost of self-collection and the risk cost of choosing cooperation, i.e., $v_s - e_s - c_s$, and her income is the basic income v_t; When they both adopt the cooperation strategy, his income depends on the RPM, cooperative risk cost, and his potential profit in a cooperative strategy, that is, $v_s - (1-\beta)l + \beta k - c_s + \Delta v_s$, and her income relies on the RPM, her operating cost of collection, her initial cost of cooperation, and her potential profit in a cooperative strategy, i.e., $v_t + (1-\beta)l - \beta k - e_t - c_t + \Delta v_t$.

If she takes the competitive strategy, his income set (competition, cooperation) is ($v_s - e_s$, $v_s - e_s - c_s$), and he will obviously choose the competitive strategy. However, if she adopts the cooperative strategy, his income set (competition, cooperation) is ($v_s - e_s$, $v_s - (1-\beta)l + \beta k - c_s + \Delta v_s$). Since the latter is bigger, he will choose to cooperate with each other. Similarly, when he chooses the cooperation strategy, she also adopts the cooperation strategy; When he adopts the competition strategy, she adopts the same one. Therefore, the pure strategy Nash equilibriums of the CEGM are (competition, competition), (cooperation, cooperation).

When both of them choose cooperation, their income set (he, she) is ($v_s - (1-\beta)l + \beta k - c_s + \Delta v_s$, $v_t + (1-\beta)l - \beta k - e_t - c_t + \Delta v_t$), which both reach the maximum value. Besides, the integration of resources caused by cooperation is beneficial to the overall interests of the RSC. Thus, the best choice for them is to adopt cooperative strategies.

In reality, when being under competition, they will vigorously pursue cooperation for greater interests. That is because he needs more remanufacturing materials and she pursues more profits. When they are under cooperation, he would doubt her operation capacity not matched with expenses, and she may dissatisfy their RPM. Therefore, it is not eternally immutable for their cooperative or competitive relationship with each other. In the long run, they will choose a competitive or cooperative strategy randomly.

4. Model Analysis and Discussion

4.1. Analysis of ESS

To obtain the evolution mechanism and the stability state of the coopetition relationship in the RSC, this paper analyzes ESSs.

It can be available from Table 3 that his expected income of cooperative strategy is:

$$E_s^c = (1-q)(v_s - e_s - c_s) + q(v_s - (1-\beta)l + \beta k - c_s + \Delta v_s), \quad (1)$$

and his expected income of competitive strategy is:

$$E_s^m = (1-q)(v_s - e_s) + q(v_s - e_s). \tag{2}$$

Then his average expectation of expected income can be showed as:

$$\overline{E_s} = pE_s^c + (1-p)E_s^m. \tag{3}$$

Similarly, her expected income of cooperative strategy is:

$$E_t^c = (1-p)(v_t - c_t) + p(v_t + (1-\beta)l - \beta k - e_t - c_t + \Delta v_t), \tag{4}$$

her expected income of competitive strategy is:

$$E_t^m = (1-p)v_t + pv_t. \tag{5}$$

Then her average expectation of expected income can be represented as:

$$\overline{E_t} = qE_t^c + (1-q)E_t^m. \tag{6}$$

The replicator dynamics [69] was used to obtain the ESS. The replicator dynamic equation of his cooperative strategy is:

$$\begin{aligned} f(p) = dp/dt &= p(E_s^c - \overline{E_s}) \\ &= p[E_s^c - (pE_s^c + (1-p)E_s^m)] \\ &= p(1-p)(E_s^c - E_s^m) \end{aligned} \tag{7}$$

Put his expected incomes into Equation (7), can obtain:

$$f(p) = p(1-p)[q(e_s - (1-\beta)l + \beta k + \Delta v_s) - c_s]. \tag{8}$$

Similarly, the replicator dynamic equation of her cooperative strategy is:

$$\begin{aligned} f(q) &= dq/dt \\ &= q(1-q)[p((1-\beta)l - e_t - \beta k + \Delta v_t) - c_t] \end{aligned}. \tag{9}$$

When $\left\{ \begin{array}{l} f(p) = 0 \\ f(q) = 0 \end{array} \right.$ is simultaneous, it can obtain $p^* = \frac{c_t}{(1-\beta)l - e_t - \beta k + \Delta v_t}$, $q^* = \frac{c_s}{e_s - (1-\beta)l + \beta k + \Delta v_s}$.

In the plane $N = \{(p, q); 0 \leq p, q \leq 1\}$, there are five equilibrium points including O (0, 0), A (0, 1), B (1, 0), C (1, 1), and M (p^*, q^*). The local stability of the RSC system is analyzed at these five equilibrium points by analyzing the local stability of Jacobian matrix. The partial derivatives of $f(p)$ and $f(q)$ are taken with respect to p and q respectively, and the Jacobian matrix is given as:

$$J = \begin{bmatrix} \frac{\partial f(p)}{\partial p} & \frac{\partial f(p)}{\partial q} \\ \frac{\partial f(q)}{\partial p} & \frac{\partial f(q)}{\partial q} \end{bmatrix} = \begin{bmatrix} b_{11} & b_{12} \\ b_{21} & b_{22} \end{bmatrix}, \tag{10}$$

where

$b_{11} = (1-2p)[q(e_s - (1-\beta)l + \beta k + \Delta v_s) - c_s]$, $b_{12} = p(1-p)[(e_s - (1-\beta)l + \beta k + \Delta v_s)]$, $b_{21} = q(1-q)[(1-\beta)l - e_t - \beta k + \Delta v_t)]$, $b_{22} = (1-2q)[p((1-\beta)l - e_t - \beta k + \Delta v_t) - c_t]$.

Denote the determinant of J as $\det J$, and $\det J = b_{11}b_{22} - b_{21}b_{12}$. Denote the trace of J as $\mathrm{tr}J$, and $\mathrm{tr}J = b_{11} + b_{22}$. According to the method proposed by Friedman [62], the criteria for judging the local stability of the Jacobian matrix are as follows:

The necessary and sufficient condition for the equilibrium point to be an evolutionary stable point is det$J > 0$, tr$J < 0$; The necessary and sufficient condition for the equilibrium point to be an instability point is det$J > 0$, tr$J > 0$; The necessary and sufficient condition for the equilibrium point to be a saddle point is tr$J = 0$.

The local stability of the equilibrium points in the RSC system can be obtained by calculation, as shown in Table 4.

Table 4. The local stability of the equilibrium points in the RSC system.

Equilibrium Point	det*J*	tr*J*	Local Stability
O (0, 0)	+	-	Evolutionary stable point
A (0, 1)	+	+	Instability point
B (1, 0)	+	+	Instability point
C (1, 1)	+	-	Evolutionary stable point
M $(p^*,\ q^*)$	+	0	Saddle point

In Table 4, "+" represents more than 0, and "-" represents less than 0.

It can be seen from Table 4 that O (0, 0), C (1, 1) are evolutionary stable points; A (0, 1), B (1, 0) are instability points; M $(p^*,\ q^*)$ is a saddle point. Therefore, the ESSs of this CEGM are (competition, competition), (cooperation, cooperation).

4.2. Coopetition Evolution Analysis

In combination with Tables 3 and 4, point A corresponds to the case where he chooses cooperation and she chooses the opposite one. Her competitive strategy is because she is not satisfied with the RPM. Point B corresponds to the case where he chooses the competitive strategy and she is the opposite. He dissatisfies with her service and adopts a competitive strategy. Their cooperation in these two cases ends in failure. However, they hope to achieve the maximization of their interests by means of cooperation. Therefore, point A and B are instability points.

Point O corresponds to the situation that they both choose competition, and point C corresponds to the cooperation situation. When they do not trust each other, they will be in competition for collection. However, when they reach an agreement, he will be not involved in the collecting business and she will provide quality services for him.

Denote his mixed strategy set as $X_1 = \{[(1-p)s_1,\ ps_2]|0 < p < 1\}$, denote her mixed strategy set of as $X_2 = \{[(1-q)s_1,\ qs_2]|0 < q < 1\}$, where s_1 represents the pure strategy of competition, s_2 represents that of cooperation. It is easy to verify that $f(p)$ is concave in p and $f(q)$ is concave in q from Equations (8) and (9), resulting in the income of $V(1-p^*,\ p^*) \geq V(1-p,\ p)$ and $V(1-q^*,\ q^*) \geq V(1-q,\ q)$ for any $0 < p < 1$ and $0 < q < 1$. According to the definition of the mixed strategy Nash equilibrium [70], when he chooses the strategy of $(1-p^*,\ p^*)$ and she chooses $(1-q^*,\ q^*)$, they are just the best response to each other, achieving the mixed strategy Nash equilibrium. Thus, $(p^*,\ q^*)$ is the mixed strategy Nash equilibrium of the CEGM.

In the long-term evolution, they will alternate the situation of competition and cooperation, and achieve a dynamic equilibrium in the saddle point M $(p^*,\ q^*)$. The evolution laws of the RSC system at different positions of point M are shown in Figure 2.

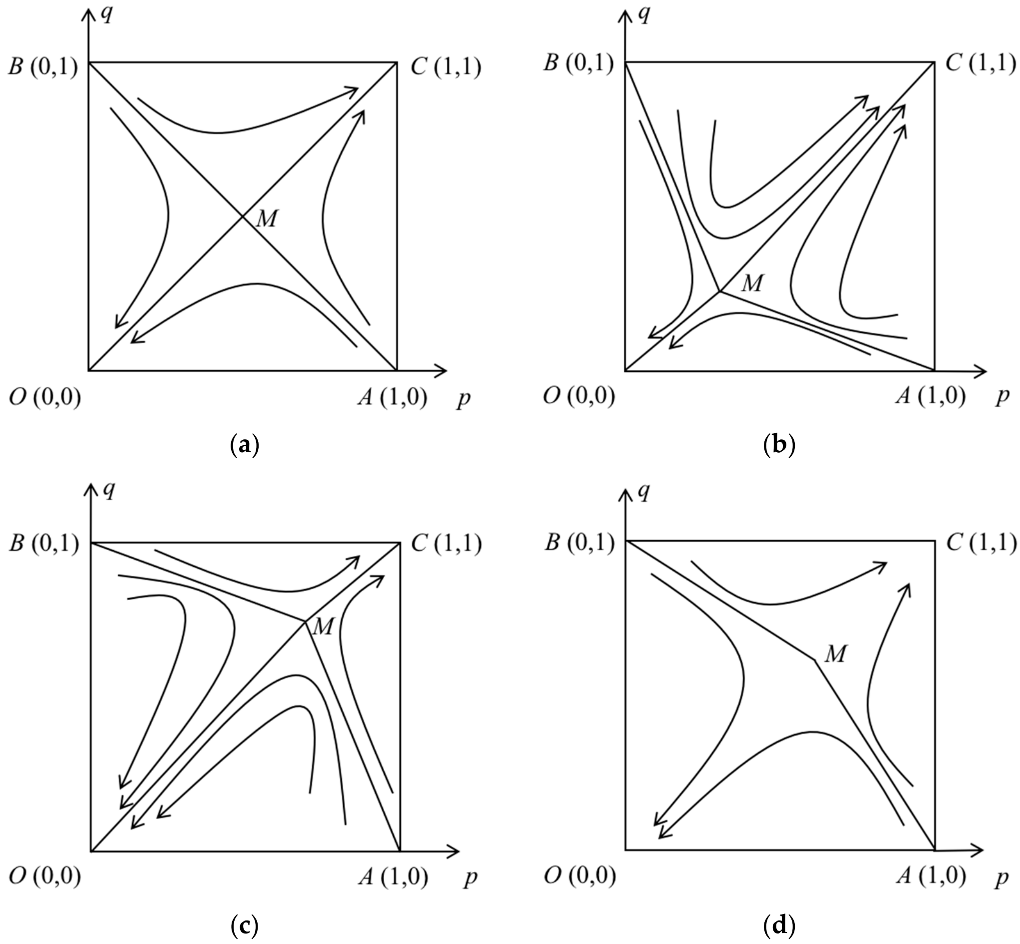


Figure 2. Evolution laws of the RSC system at different positions of point M: (**a**) M is in ($p^* = 0.5$, $q^* = 0.5$). (**b**) M is in ($p^* < 0.5$, $q^* < 0.5$). (**c**) M is in ($p^* > 0.5$, $q^* > 0.5$). (**d**) M is to be determined.

In Figure 2a, the point M is in the position (0.5, 0.5), and they have the same probability of overall competition or cooperation here; The point M is in the position ($p^* < 0.5$, $q^* < 0.5$) in Figure 2b, and they are more convergent to point C (**cooperation**), that is, more likely to choose the comprehensive cooperation strategy; In Figure 2c, it is in the position ($p^* > 0.5$, $q^* > 0.5$), and here they are more convergent to point O (**competition**), namely, more likely to choose overall competition; The position of point M is to be determined in Figure 2d, and it is necessary to determine whether the system converges to point O or point C by means of further analysis.

Denote the area of quadrilateral $AMBO$ as S_1, the area of quadrilateral $AMBC$ as S_2. Then

$$S_1 = \frac{1}{2}(1 \times p^*) + \frac{1}{2}(1 \times q^*) = \frac{1}{2}\left[\frac{c_t}{(1-\beta)l - e_t - \beta k + \Delta v_t} + \frac{c_s}{e_s - (1-\beta)l + \beta k + \Delta v_s}\right], \tag{11}$$

$$S_2 = 1 - S_1 = 1 - \frac{1}{2}\left[\frac{c_t}{(1-\beta)l - e_t - \beta k + \Delta v_t} + \frac{c_s}{e_s - (1-\beta)l + \beta k + \Delta v_s}\right]. \tag{12}$$

The probability of the system convergence to the equilibrium point O is higher than C when $S_1 > S_2$, as shown in Figure 2c; The probability of the system convergence to O is lower than C when $S_1 < S_2$, as shown in Figure 2b; The probability of the system convergence to O is equal to C when $S_1 = S_2$, as shown in Figure 2a. Therefore, the probability of their competition is positively related to S_1, and the probability of cooperation is positively related to S_2.

It can be seen from Equations (11) and (12) that the factors that influence S_1 and S_2 are Δv_s, Δv_t, c_s, c_t, e_s, e_t, l, k, and β in this game model. The detailed analysis will be presented below.

4.3. Sensitivity Analysis

Combining Equations (11) and (12) and the previous model assumptions, we can get the sensitivity analysis of the related parameters in the CEGM, as illustrated in Table 5.

Table 5. Sensitivity analysis of the related parameters in the CEGM.

	Δv_s	Δv_t	c_s	c_t	e_s	e_t	l	k	β
S_1	−	−	+	+	−	+	$(\mp)^*$	$(\mp)^\sim$	$(\mp)^\#$
S_2	+	+	−	−	+	−	$(\pm)^*$	$(\pm)^\sim$	$(\pm)^\#$
Probability of cooperation	+	+	−	−	+	−	$(\pm)^*$	$(\pm)^\sim$	$(\pm)^\#$

In Table 5, the signs + and − represent an increase and decrease in equilibrium, in response to a marginal increase of the corresponding parameter, respectively. The sign $\pm$ indicates that the equilibrium climbs up and then declines with a marginal increase of the corresponding parameter; The sign $\mp$ indicates that the equilibrium decreases first and then increases with a marginal increase of the corresponding parameter. The superscripts $*$, $\sim$, # denote the different turning points of corresponding parameters.

As shown in Table 5, the bigger Δv_s, the smaller S_1 and the bigger S_2, that is, the probability of the system convergence to O is smaller, but to C is greater. Similarly, the bigger Δv_t, the smaller the probability of the system convergence to O and the greater to C. That means the greater the potential profit, the smaller the barrier to cooperation, and the probability of the waste phone RSC system evolved into cooperation is greater. It implicates that she should increase the collection quantity and quality of WMPs, and he should comply with the contract of cooperation.

The bigger c_s, the bigger S_1 and the smaller S_2, namely, the probability of the system convergence to O is greater, but to C is smaller. Similarly, the bigger c_t, the greater the probability of the system convergence to O and the smaller to C. In other words, the greater the initial cost or risk cost of the cooperation strategy, the lower the willingness to cooperate, and the probability of the system evolved into competition is greater. It shows that she should improve operational management capability to reduce the risk cost of his cooperation strategy. She should also make full use of their resources, for example, take advantage of his sales outlets to conduct collection. He should evaluate her carefully according to her contractual history and operational capability.

The greater the operating cost of his self-collection e_s and the smaller the operating cost of her collection e_t, the greater the willingness to cooperate, and the probability of the system evolved into cooperation is greater. It indicates that she should improve operational management capability to reduce her operating costs.

The greater his reward to her, the greater the probability of her cooperation, but the smaller that of his cooperation. The greater his penalty to her, the smaller the probability of her cooperation, but the greater one of his cooperation. That means there are some contradictions that complicate the effects of the reward implemented by him for her successful service l and the penalty implemented by him for her failed service k on the probability of cooperation. These contradictions implicate that they have an optimal RPM to promote the cooperation tendency. As shown in Table 5, S_1 decreases first and then increases as l or k increases, and S_2 is the opposite, namely, the system first tends to converge to C and then to O. In this case, both l and k have an optimal value, making the probability of the system evolved into cooperation to the maximum. The probability of her service failure β has a direct impact on the implementation of l and k, and its change is consistent with k.

It can be obtained by solving Equation (11) that the optimal reward implemented by him for her successful service l is $\frac{(e_s+\beta k+\Delta v_s)(c_t-\sqrt{c_s c_t})+(e_t+\beta k-\Delta v_t)(\sqrt{c_s c_t}-c_s)}{(1-\beta)(c_t-c_s)}$, and the optimal penalty implemented by him for her failed service k is $\frac{[(1-\beta)l-e_t+\Delta v_t](c_s-\sqrt{c_s c_t})+[e_s-(1-\beta)l+\Delta v_s](c_t-\sqrt{c_s c_t})}{(c_s-c_t)\beta}$. The probability of her service failure that is most conducive to cooperative evolution β is $\frac{(l-e_t+\Delta v_t)(c_s-\sqrt{c_s c_t})+(e_s-l+\Delta v_s)(c_t-\sqrt{c_s c_t})}{(l+k)(c_s-c_t)}$.

In conclusion, the optimal RPM is $l = \frac{(e_s+\beta k+\Delta v_s)(c_t-\sqrt{c_s c_t})+(e_t+\beta k-\Delta v_t)(\sqrt{c_s c_t}-c_s)}{(1-\beta)(c_t-c_s)}$, $k = \frac{[(1-\beta)l-e_t+\Delta v_t](c_s-\sqrt{c_s c_t})+[e_s-(1-\beta)l+\Delta v_s](c_t-\sqrt{c_s c_t})}{(c_s-c_t)\beta}$.

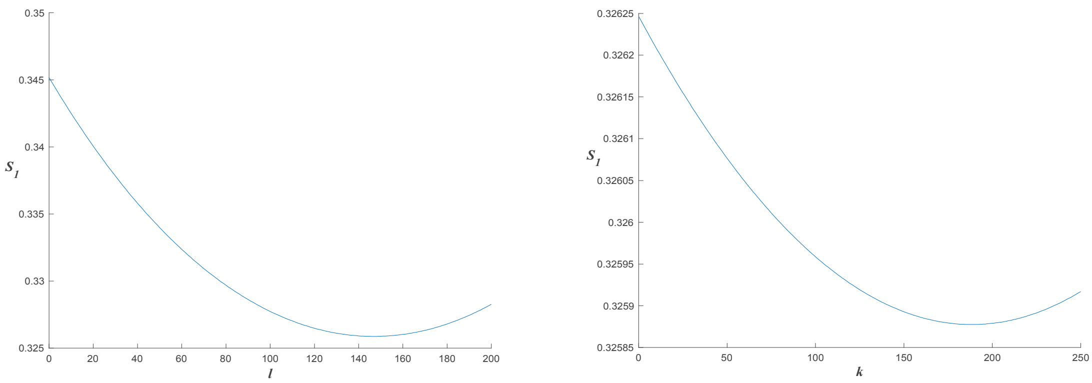
5. Simulation of RPM

Although the theoretical solution of the optimal RPM has been analyzed in Section 4.3, to enhance understanding, a simulation of the RPM is conducted to further clarify the meaning of the optimal RPM. Therefore, we investigated a famous mobile phone manufacturer A and a prosperous third-party collector B as a case study. The parameters, as shown in Table 6, in the following simulation experiments were collected from them, but were modified for the confidentiality reason. These experiments were conducted on the simulation platform of MATLAB R2017b.

Table 6. The simulation parameters' value.

Parameters	v_s	v_t	c_s	c_t	e_s	e_t	Δv_s	Δv_t	l	k	β
Values	1800	1200	185	180	100	90	580	530	150	160	0.1

To obtain the optimal reward implemented by him for her successful service l, we made the range of l 0–200, and the simulation result is shown in Figure 3a. Similarly, to obtain the optimal penalty implemented by him for her failed service k, we made the range of k 0–250, and the result is shown in Figure 3b.



(**a**) (**b**)

Figure 3. (**a**) Simulation of S_1 varying with l. (**b**) Simulation of S_1 varying with k.

It can be seen from Figure 3a that S_1 decreases first and then increases as l increases. In this case, when $l = 150$, the value of S_1 is the minimum, that is, it is the largest for the probability of the system evolved into cooperation. k has the similar effect on S_1 as l, which is shown in Figure 3b. When $k = 190$, the value of S_1 is the minimum in this case, namely, it is the largest for the probability of the system evolved into cooperation.

We also made the simulation of S_1 with the ranges of l 0–200 and k 0–250, the result is shown in Figure 4.

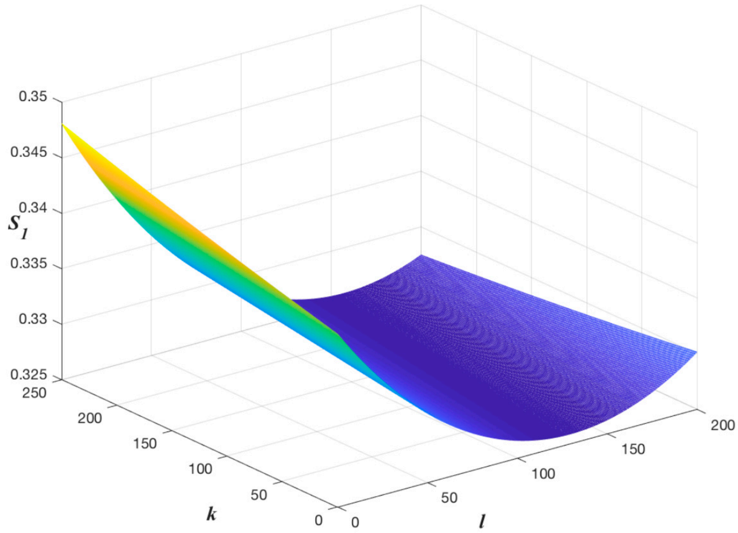


Figure 4. Simulation of S_1 varying with l and k.

It can be seen from Figure 4 that S_1 is under the double influence of l and k. When l is low, S_1 increases with the increase of k, otherwise, S_1 decreases with the increase of k. However, S_1 decreases first and then increases as l increases no matter whether k is big or small. It shows that the optimal RPM consisting of the optimal reward and penalty is interrelated, and they need to be developed at the same time, which is the same as the implication of their formulas. According to the calculated results, the optimal reward and penalty here are 147 and 143, respectively.

6. Conclusions, Insights, and Future Research

This paper presents a CEGM to discuss the coopetition relationship between members in an RSC comprising one manufacturer and one collector and examines the evolution mechanism and the internal RPM for their collection strategies. The pure strategy Nash equilibriums in this model are obtained which show their collection strategy choices of perfect competition or cooperation. However, their cooperative or competitive relationship is not eternally immutable. In the long run, they will choose a competitive or cooperative strategy randomly. The mixed strategy Nash equilibrium and the optimal RPM are obtained in the model analysis and discussion. Finally, this paper takes the example of WMPs in China to examine the simulation of the RPM.

The contributions of this paper include two parts: Firstly, it examines the coopetition relationship between the manufacturer and the collector. It provides common collection strategies and then analyzes the evolution of them, which is of practical significance to implement their collection of WMPs. Secondly, it discusses the two-sided RPM negotiated by the manufacturer and the collector in the RSC, which is beneficial to promote their cooperation tendencies and then to increase their payoffs.

We find that cooperation is the best choice for the manufacturer and the collector to increase their payoffs. There is an optimal RPM for them to propel the cooperation tendency. We provide some practical insights for the manufacturer and the collector as follows. They need to simultaneously negotiate the two-sided RPM consisting of the optimal reward and penalty. The manufacturer should evaluate the potential partner carefully according to her contractual history and operational capability. Once cooperation is reached, he should faithfully perform it. The collector should improve operational management capability to reduce her operating costs and the risk cost of his cooperation strategy and to increase the collection quantity and quality of WMPs. She should also make full use of their resources, for example, take advantage of his sales outlets to conduct collection.

This paper adopts the failure probability of the collector's service instead of the quantitative analysis of her service to define her success or failure. However, the latter is more feasible to implement the RPM, because to obtain the failure probability of her service needs accurate evaluation and prediction. Thus, the future research should quantitatively analyze her service and provide more specific RPM. In addition, other competitors are neglected in this paper, it is more practical to deal with internal and external competition from members in the RSC.

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Appendix A

Table A1. List of acronyms.

Acronym	Explanation
WMPs	Waste mobile phones
RPM	Reward-penalty mechanism
WEEE	Waste electrical and electronic equipment
EPR	Extended producer responsibility
RSC	Reverse supply chain
PROs	Producer responsibility organizations
EGT	Evolutionary game theory
CLSC	Closed-loop supply chain
CEGM	Coopetition evolutionary game model
ESS	Evolutionary stability strategy
OFN	Old-for-New

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