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Abstract: With the number of energy vehicles increases, so does the quantity of used batteries. However, the stakeholders of the new energy battery supply chain, so far, have not been able to take responsibility for recycling. In this study, the influence of different subsidy strategies adopted by the government on the determination of each participant in the new energy battery supply chain is determined in the case of government participation and anarchy participation. We observed different strategies for government involvement, such as government recycling subsidies, profit reward and punishment policies, and total recovery costs and profits. At the same time, we designed a game strategy. This strategy shows that in the case of interaction between recyclers and manufacturers, the higher the additional income of recyclers and the degree of cooperation of manufacturers to participate in recycling processing, the higher the compensation for non-partners, and the recyclers and manufacturers are more inclined to increase the level of recycling. Compared with no subsidies and no government participation, government participation can improve the recycling rate of used batteries and the profits of enterprises. Our work provides decision support for government involvement in the energy vehicle supply chain.

Keywords: New Energy Vehicle Battery; Government Intervention; Evolutionary Game Theory; Reverse Supply Chain (RSC); Penalty Measures; Simulation

1. Introduction

Due to the quasi-externality of battery recycling in energy vehicles, there are large investments in new technologies and developments. There is also a need for more technical personnel and better definitions of the recycling network and system at the initial stages. Generally, recycling enterprises cannot fully assume the responsibility of recycling, and there needs to be more motivation to create a high-quality recycling model. The government's macro-control is vital.

Game theory-based research is notably extensive in the battery recycling of energy vehicles. Zhang et al.(2022) constructed the evolutionary game model of waste battery recycling supervision. They solved and analysed the evolutionary stable equilibrium strategy of waste battery recycling and remanufacturing and step-by-step utilisation in battery production enterprises under the government's policy of reducing subsidies yearly. Li et al. (2022) examined the evolutionary equilibrium strategies of participants in the e-waste recycling governance game under government supervision. This analysis was conducted through the construction of an evolutionary game model involving manufacturers, recycling enterprises, and the government. However, the existing research mostly analyses each strategy's stability from each player's perspective in the three-way game analysis. It needs to include the overall analysis of the strategy combination in the game system. Lyapunov's first method is a foundational method employed in modern cybernetics for analyzing the stability of differential equations. Lu Zhengyu (2018) analysed the stability of mechanical operating systems. It is rarely used to analyse the stability of a three-party evolutionary game system. For example, Guo Benhai and Wang Han used Lyapunov's first method to analyse the stability of a three-group evolutionary game's pure strategy equilibrium point. Rong Junmei and Zhu Lilong (2020) combined Lyapunov's first method to analyse and simulate the stability of the equilibrium point of the game system. It can be seen that most of the existing studies ignoring the analysis of mixed strategy equilibrium points.

The academic research on the government's reward and punishment policy on Reverse Supply Chain (RSC) has greatly improved the recovery rate of energy vehicles. From the perspective of subsidy policy types, Li et al.(2020) based on Shenzhen's work on battery recycling subsidy policy, applied system dynamics to analyse the influence of the deposit refund system on the battery recycling of energy vehicles. Zhu et al. (2020) studied the optimal decision-making problem of each member under different subsidy objects under the closed-loop supply chain of dual-channel recycling. From the perspective of recycling mode, Zhang et al. (2021) compared and analysed the influence of reward and punishment mechanisms on battery recycling of energy vehicles. There are also a few scholars who have compared different recycling policies. Tang (2019) and others have comparatively analysed the influence of the subsidy, reward and punishment mechanism on the recycling of power batteries and found that when the recycling cost is low, the reward and punishment mechanism has a greater influence on the recycling rate and social welfare than the subsidy mechanism. Although the literature shows that the reward and punishment mechanism is superior to the subsidy mechanism under certain conditions, it does not consider different types of subsidy policies under different subsidy standards. Therefore, it is still necessary to study the subsidy mechanism further.

In summary, scholars have generally discussed the factors that affect the decision-making of power battery RSC, including contract coordination, market competition, recycling policy, etc. The contributions of this paper are as follows: (1) Based on the existing RSC, this paper compares and analyses whether there are government subsidies and reward and punishment policies and discusses the influence of government on battery recycling of energy vehicles; (2) Explore the effect mechanism and different levels of different recycling subsidies, reward, punishment policies on recycling profits, recycling costs, total recycling costs and total recycling profits of recyclers and manufacturers.

The rest of the paper is organised as follows: the second section introduces the relevant literature review, and the third section establishes the game model. From different subjects, the game models of recycler, manufacturer and government, recycler and manufacturer are established. And the game results are analysed and simulated. The fourth section explores decision support and suggests targeted strategic suggestions for government intervention. The fifth section summarises and looks forward to the research results of this paper.

2. Literature review

2.1 The development and application of RSC

With the advancing green economy and the rise of environmental conservation principles, Zarbakhshnia (2020) and more scholars have incorporated environmental factors into the supply chain design and developed an RSC. The RSC can improve the environment and greatly benefit the company's development. Through an RSC, Sauer and Seuring (2018), Kannan (2018), Govindan et al. (2020) created a corporate image that protects the environment, gains marketing advantages, reduces costs, and improves customer relations.

The main body of the RSC mainly includes consumers, recyclers, manufacturers, remanufacturers and third-party logistics. Many scholars have discussed the cost and profit of an RSC. Fu et al. (2021) put forward the supply chain circulation mode of forward and RSCs, and how the raw material cost in forward supply chain and RSC affects the demand, balanced price and total profit of RSC. Ullah et al. (2021) considered the remanufacturing link in the RSC, the research shows that manufacturing and remanufacturing costs play a decisive role in the remanufacturing rate of products, and improving the remanufacturing rate can reduce the system setup cost and ordering cost. Ghavamifar et al. (2018), Rezapour et al. (2017), Liao (2018) and Trochu et al. (2018) studied how to maximise the profit of RSC, while Kannan (2021), Kusakct et al. (2019), Doan et al. (2019) and Paydar et al. (2018) focused on minimising the cost of RSC.

In the RSC of waste energy vehicle batteries, many scholars have been studying the recycling subject, improving the recovery rate, and putting forward many novel opinions. Liu et al. (2021) made an evolutionary game study on the alliance and cooperation between China's main bodies of power battery recycling of energy vehicles. They proposed a recycling policy combining subsidies with supervision or phased supervision to promote effective recycling. Karakayai et al. (2007) studied that the Original Equipment Manufacturer (OEM) outsourced recycling and found that when the product’s homogeneity is high, the recycler can maximise the recycling rate. Kaya (2010) toke the recycling price and quantity as evaluation indicators and studies the situation of direct recycling by remanufacturers and third-party recycling under three modes. Liu et al. (2017) studied three different recycling systems and finally concluded that cooperation between OEMs and recyclers is the best choice. The research on RSC mainly focuses on the right structure, cost, profit and third-party logistics evaluation of RSC, and the comparative analysis of different recycling policies needs to be improved in the future.

2.2 The influence of government subsidies and supervision on RSC

In recent years, the oversight conducted by the government on the environment has aroused widespread concern among researchers, and governments of various countries have reached many agreements on environmental legislation and responsibilities. The government mainly plays two roles in the RSC. One is to punish enterprises that do not participate in the RSC through environmental tax; The other is to reward enterprises through tax relief or subsidies.

Madani and Rasti-Barzoki (2017) observed that the impact of increasing the subsidy rate by the government is far greater than the tax rate, and the development of RSC will increase the government's and supply chain's profits. He and Wu (2016) proposed three government subsidy mechanisms for manufacturers and obtained the conditions for different subsidy policies to maximise social welfare and profits. Jafar and Kannan (2017) analysed the role of different government subsidy strategies in coordinating the supply chain.

Compared with the tax-subsidy mechanism, Chen et al. (2022) put forward that pollution tax, low-carbon technological innovation subsidy and environmental protection publicity and guidance are three kinds of environmental regulation means to effectively stimulate enterprises' green and low-carbon technological innovation.

2.3 The application of evolutionary game in RSC cooperation

Evolutionary game theory is a theoretical method combining analysis employing game theory a dynamic evolution process and discusses how bounded rational participants make decisions under incomplete information (Friedman, 1998). In evolutionary games, the strategies of both participants will eventually converge to the Evolutionary Stable Strategy (ESS) (Friedman, 1991). This method emphasises the system's dynamic balance and has great potential to simulate actual economic problems (Fang et al., 2020). Many scholars use evolutionary game theory to solve problems in various fields, including economics (Sohrabi and Azgomi, 2019), computer science (Hosseini-Motlagh et al, 2020), and management. From the perspective of game subjects, current research literature can be divided into two-party games and multi-party games.

Mahmoudi and Rasti-Barzoki (2018) considered three different objective Eq.s, established an evolutionary game model between the government and manufacturers and analysed the influence of government policies on manufacturers' behaviour and carbon emissions. Tu et al.(2020) established a three-way game model to analyse the dynamic evolution process among EPA, manufacturers and consumers. Zhang et al. (2019) studied the effects of the carbon trading market, environmental tax and innovation on the evolutionary results.

Currently, some scholars have applied evolutionary game theory to study the green and low-carbon development model of the government, upstream and downstream enterprises in RSC and other stakeholders and to explore the interaction mechanism of each subject in the game system. However, the existing research mostly analyses each strategy's stability from each player's perspective in evolutionary game analysis. Still, it needs the overall analysis of strategy combination in a game system.

3. Problem description

The RSC of energy vehicle batteries starts from manufacturers to retailers, retailers to consumers, consumers to recyclers, and then to manufacturers for remanufacturing. When a product has completed its whole life cycle but still has huge surplus value, it will be recycled from consumers in some way and then remanufactured to make it reused. Closed-loop supply chain recycling can cancel resources, reduce energy consumption and carbon emissions, and improve enterprises' profits and overall benefits (Fig. 1).

As shown in Fig. 1, the RSC constructed in this article contains the following partial structures.

Battery manufacturer: Buys nickel, cobalt and other raw materials from the market to produce brand-new power batteries while recycling and reprocessing materials from battery recyclers. When battery manufacturers choose to maintain the status and not improve the battery recycling level of energy vehicles, they must pay government fines and environmental taxes. When battery manufacturers choose to improve the recycling level of energy vehicles, the government will give subsidies and incentives. Still, battery manufacturers must also bear the cost of improving the recycling cycle.

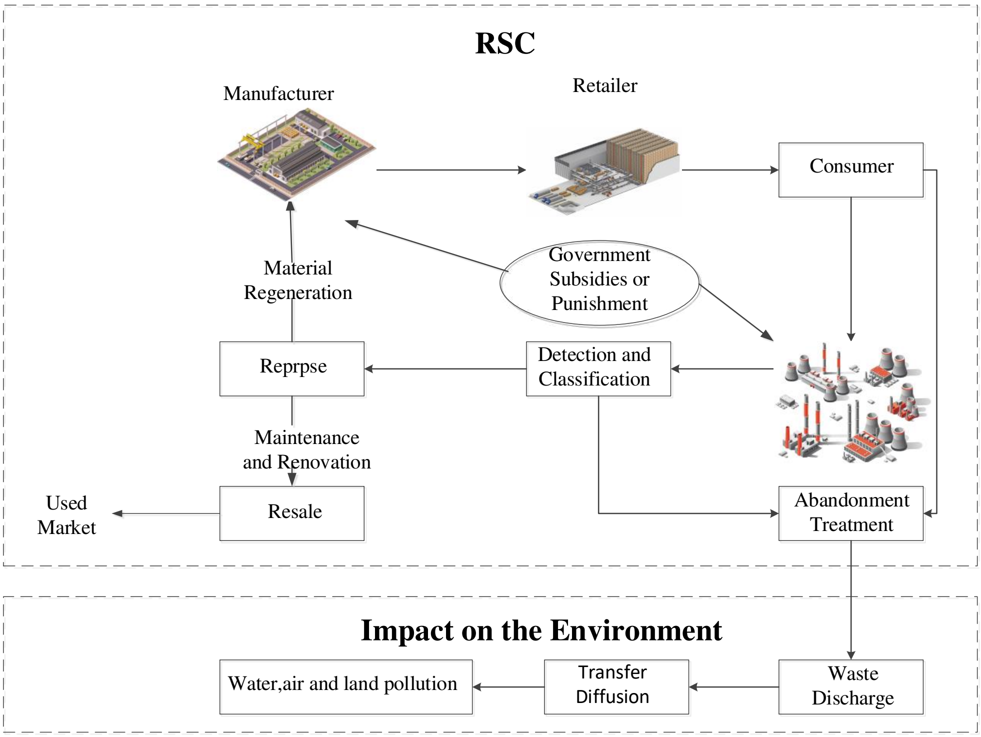

Fig. 1. The RSC of new energy vehicle batteries

Recycler: Recovers the retired new energy automobile batteries from consumers for a fee, then tests, classifies, reprocesses, and sells them to battery manufacturers. When the battery recycling option maintains the status quo and does not improve the battery recycling level of energy vehicles, it is necessary to pay fines and environmental taxes to the government. The situation is similar to that of the manufacturers: when battery recyclers choose to improve the battery recycling level of energy vehicles, the government will give subsidies and incentives. Still, battery manufacturers must also bear the cost of improving the recycling level.

Government: Regulators outside the supply chain, advocating to maximise social interests. They can choose to actively take subsidy measures for battery manufacturers and battery recyclers and subsidise battery manufacturers and recyclers in the battery recycling supply chain. The government can also reap the benefits of environmental improvement, but the government needs to bear the subsidy cost. Or by raising taxes and collecting fines to improve the recovery rate of retired car batteries, the government will pay the additional cost of environmental remediation.

After several years of use, batteries of energy vehicles reach the scrapping standard and can be recycled by enterprises at this time. In the supply chain system for recycling new energy vehicle batteries, which consists of recyclers and manufacturers, the government needs to subsidise and supervise the enterprises involved in recycling new energy vehicle batteries with high recycling costs and complicated recycling processes. When enterprises choose not to recycle discarded new energy automobile batteries actively, they need to bear the public environmental impact of the products on society, and enterprises should pay corresponding environmental protection taxes to make up for the negative externalities caused by new energy automobile batteries to the environment.

This paper formulates a two-party game model between recyclers, manufacturers and a three-party game model between the government, recyclers and manufacturers to study the influence of government subsidies and supervision on the recovery rate and the recovery decision of both parties without government participation.

4. The evolutionary game model of recycler-manufacturer

4.1 Assumptions and Parameters

In our model, manufacturers collect energy automobile batteries from recyclers. Both manufacturers and recyclers take the maximisation of their interests as the premise of the recycling process, and the strategies made by the two participants will affect each other. In the evolution process of recycling from electric vehicles, the two participants are bounded and rational, and there is a phenomenon of information integration between them, which makes it impossible for recyclers and manufacturers to determine whether their decisions can bring them the greatest benefits.

Through the above evaluation of the evolutionary game for the main body of the energy vehicle battery, the following assumptions are made:

Hypothesis 1: The battery recycling cost of different models of energy vehicles is the same.

Hypothesis 2: With recyclers and manufacturers as participants, the two participants are bound and rational in the evolutionary game of battery recycling in energy vehicles.

Hypothesis 3: Before the cooperation, the normal income of recyclers and manufacturers was I_R and I_M .

Hypothesis 4: Between the recycler and the manufacturer, if one of them does not cooperate, it is necessary to pay some compensation K to the other party who cooperates.

Hypothesis 5: The probability that recyclers choose the strategy of "improving reuse level" is y, and the probability of choosing the strategy of "maintaining the status is $1-y$; The probability that the manufacturer chooses the strategy of "improving the reuse level" is z, and the probability that the manufacturer chooses the strategy of "maintaining the status is $1-z$, in which $0 \le y, z \le 1$.

Additional parameters are shown Table 1:

Table 1 Parameter compliance and explanation

Parameter symbol	Explanation
I_R	Normal income of recyclers before cooperation.
I_M	Normal earnings of manufacturers before cooperation.
C_R	Costs incurred by recyclers when they choose the strategy of "improving reuse level."
C_M	Costs incurred by manufacturers when they choose the strategy of "improving reuse level."
C	The total cost generated by the cooperation between recyclers and manufacturers is as follows: α and $1\text{-}\alpha$ $(0<\alpha<1)$
S	The recycler and the manufacturer choose to cooperate to recycle the extra income, and the proportion of the two is β and $1-\beta(0<\beta<1)$
K	Compensation paid by the uncooperative party to the cooperative party.

4.2 Stability analysis of equilibrium solution

According to the Malthusian equation, the replication dynamic equation of the strategy selection of the recycler is:

$$F(y)=\frac{dy}{dt}=y(M_{E1}-\overline{M_E}) \tag{1}$$

The manufacturer's reproducible dynamic equation:

$$F(z)=\frac{dz}{dt}=z(1-z)\left\{\left[(1-\beta)S-(1-\alpha)C+C_M\right]y+K-C_M\right\} \tag{2}$$

A two-dimensional decision-making equation set is obtained simultaneously from the recycling quotient and the replication dynamic equation of manufacturing:

$$\begin{cases} F(y)=\dfrac{dy}{dt}=y(1-y)\left[(\beta S+C_R-\alpha C)z+K-C_R\right]=0 \\ F(z)=\dfrac{dz}{dt}=z(1-z)\left\{\left[(1-\beta)S-(1-\alpha)C+C_M\right]y+K-C_M\right\}=0 \end{cases} \tag{3}$$

By solving y and z, we can get five equilibrium points of the model, namely:

$$(0,0),(0,1),(1,0),(1,1),\left(\frac{C_M-K}{(1-\beta)S-(1-\alpha)C+C_M},\frac{C_R-K}{\beta S-\alpha C+C_R}\right)$$

Further, according to the analysis method of local stability proposed by Friedman, the differential equations about y and z are calculated, and the corresponding Jacobian matrices are listed, namely:

$$J_2=\begin{bmatrix} \dfrac{\partial F(y)}{\partial y} & \dfrac{\partial F(y)}{\partial z} \\ \dfrac{\partial F(z)}{\partial y} & \dfrac{\partial F(z)}{\partial z} \end{bmatrix}$$

$$=\begin{bmatrix} (1-2y)\left[(\beta S+C_R-\alpha C)z+K-C_R\right] & y(1-y)(\beta S+C_R-\alpha C) \\ z(1-z)\left[(1-\beta)S-(1-\alpha)C+C_M\right] & (1-2z)\left\{\left[(1-\beta)S-(1-\alpha)C+C_M\right]y+K-C_M\right\} \end{bmatrix}$$

(4)

Among them:

$$tr(J_2)=(1-2y)\left[(\beta S+C_R-\alpha C)z+K-C_R\right]+(1-2z)\left\{\left[(1-\beta)S-(1-\alpha)C+C_M\right]y+K-C_M\right\}$$

(5)

$$\det(J_2)=\begin{vmatrix} (1-2y)\left[(\beta S+C_R-\alpha C)z+K-C_R\right] & y(1-y)(\beta S+C_R-\alpha C) \\ z(1-z)\left[(1-\beta)S-(1-\alpha)C+C_M\right] & (1-2z)\left\{\left[(1-\beta)S-(1-\alpha)C+C_M\right]y+K-C_M\right\} \end{vmatrix}$$

(6)

The equilibrium point is the Evolutionary Stable Strategy (ESS) only when these conditions are met.

For the above five equilibrium points

$$(0,0),(0,1),(1,0),(1,1),\left(\frac{C_M-K}{(1-\beta)S-(1-\alpha)C+C_M},\frac{C_R-K}{\beta S-\alpha C+C_R}\right)$$

Calculate the expressions of its determinant and trace respectively to judge whether it is stable, in which

$$(y^0,z^0)=\left(\frac{C_M-K}{(1-\beta)S-(1-\alpha)C+C_M},\frac{C_R-K}{\beta S-\alpha C+C_R}\right)$$

The relationship between parameters and the equilibrium points of the model under different constraints is discussed. There are nine situations, namely:

(1) $(1-\beta)S-(1-\alpha)C+C_M>0,\beta S-\alpha C+C_R>0,C_M<K,C_R<K$

(2) $C_M<K,0<C_R-K<\beta S-\alpha C+C_R$

(3) $C_M<K,0<\beta S-\alpha C+C_R<C_R-K$

(4) $C_M>K>(1-\alpha)C-(1-\beta)S,C_R<K$

(5) $C_M>K>(1-\alpha)C-(1-\beta)S,0<C_R-K<\beta S-\alpha C+C_R$

(6) $C_M>K>(1-\alpha)C-(1-\beta)S,0<\beta S-\alpha C+C_R<C_R-K$

(7) $C_M>K,K<(1-\alpha)C-(1-\beta)S,C_R<K$

(8) $C_M>K,K<(1-\alpha)C-(1-\beta)S,0<C_R-K<\beta S-\alpha C+C_R$

(9) $C_M>K,K<(1-\alpha)C-(1-\beta)S,0<\beta S-\alpha C+C_R<C_R-K$

Based on the above nine conditions, the determinant and trace size of the Jacobian matrix J_2 at five equilibrium points can be obtained to judge its local stability. The evolution path diagram of the system is shown in the **Fig. 2**, in which the horizontal axis Y represents the probability that the recycler chooses the strategy of "improving the treatment level", and the vertical axis Z represents the probability that the manufacturer chooses the strategy of "improving the treatment level".

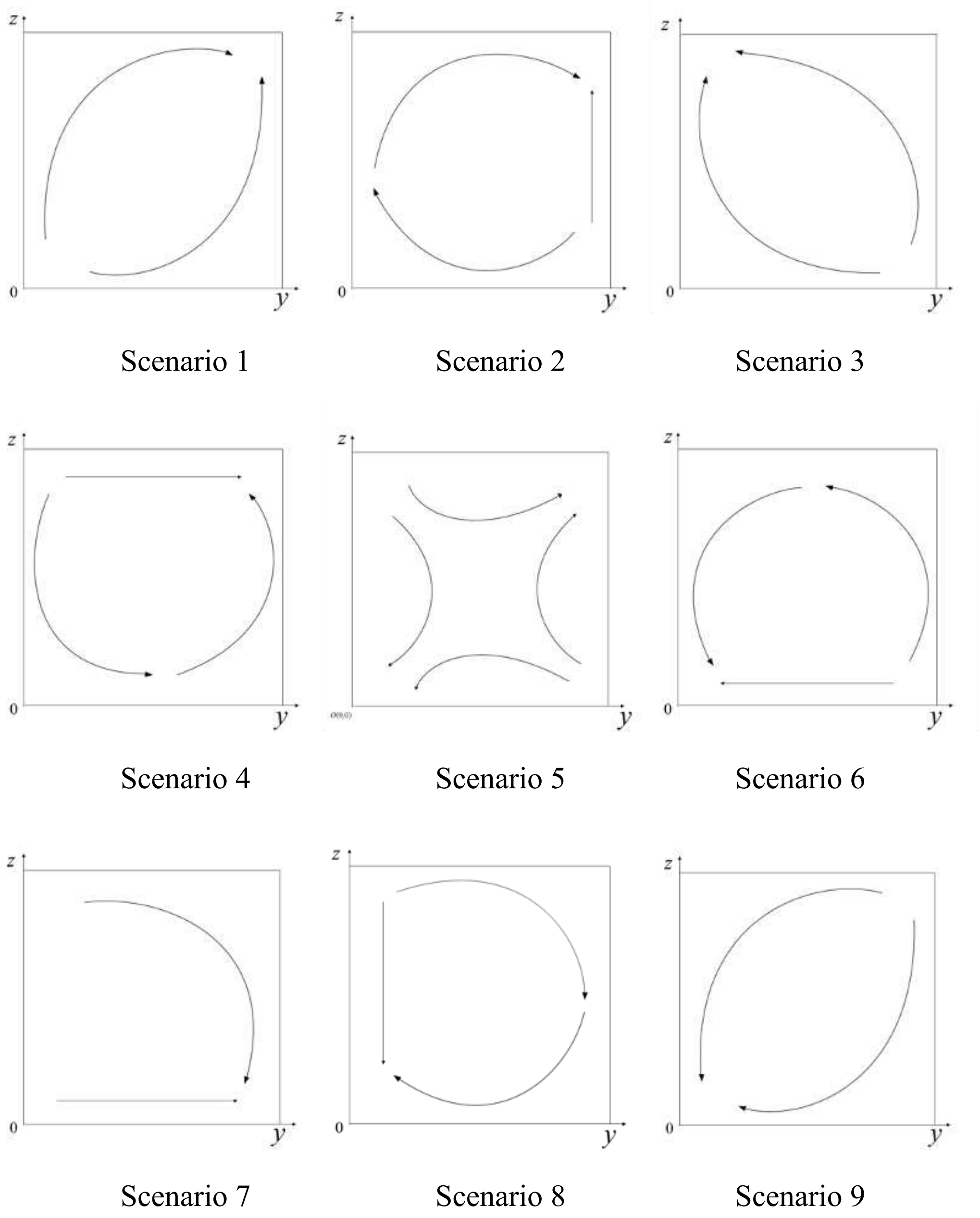

Fig. 2. The evolution path diagram of the system in cases 1-9

The above Table 2 shows that the parameters have different stable points under different constraints.

Table 2. Different stability points under different constraints

Situation	Constraint condition	Stable point
1	$C_M > K > (1-\alpha)C-(1-\beta)S, 0 < C_3 - K < \beta S - \alpha C + C_R$ $C_M > K > (1-\alpha)C-(1-\beta)S, 0 < \beta S - \alpha C + C_R < C_R - K$ $C_M > K, K < (1-\alpha)C-(1-\beta)S, 0 < C_R - K < \beta S - \alpha C + C_R$ $C_M > K, K < (1-\alpha)C-(1-\beta)S, 0 < \beta S - \alpha C + C_R < C_R - K$	(0,0)
2	$C_M < K, 0 < \beta S - \alpha C + C_R < C_R - K$	(0,1)
3	$C_M > K, K < (1-\alpha)C-(1-\beta)S, C_R < K$	(1,0)
4	$(1-\beta)S-(1-\alpha)C+C_M > 0, \beta S - \alpha C + C_R > 0, C_M < K, C_R < K$ $C_M < K, 0 < C_R - K < \beta S - \alpha C + C_R$ $C_M > K > (1-\alpha)C-(1-\beta)S, C_R < K$ $C_M > K > (1-\alpha)C-(1-\beta)S, 0 < C_3 - K < \beta S - \alpha C + C_R$	(1,1)

We can get the conclusions:

(1) For situation 1, after both parties choose to participate in recycling at first, the income brought to them by active participation βS and $(1-\beta)S$ is less than the average recycling cost, making both parties lose the motivation to participate actively. (0,0) is the stable point of the two-party game; that is, it is an evolutionarily stable

strategy for recyclers and manufacturers not to invest in recycling subsidies. In the early stage of development, because recyclers and manufacturers have no recycling experience and perfect recycling channels, they need to invest a lot of money to build recycling infrastructure. During this period, the income increase rate of participating in recycling is very low. Moreover, there is a lack of reference objects in the early stage of RSC, and investment recovery is very risky. If there are no incentive measures from government agencies, recyclers and manufacturers will choose not to participate in recycling to ensure their respective benefits and avoid the risk of losing recycling.

(2) For situation 2, (0,1) is the stable point of the two-player game. As for recyclers, when $C_R > K$, $\beta S - \alpha C + C_R > 0$, recyclers choose to improve the reuse level, the benefits and subsidies they get are less than the costs they pay. Recyclers will not take the initiative to improve utilisation to save costs and improve economic benefits. From the manufacturer's point of view, $C_M < K$, when the manufacturer improves the recycling level, the economic subsidy is greater than the cost, so the manufacturer will choose to improve the recycling level, thus improving its sustainable development ability. Therefore, the final stable result is (maintaining the status quo and improving the level of reuse). When the manufacturer gives full play to its production advantages and establishes a perfect recycling channel, its recycling will create greater benefits for it, so the manufacturer will actively recycle and expand the recycling scale. However, due to its characteristics, recyclers must pay a huge cost to form a perfect recycling channel, so recyclers will not recycle.

(3) For situation 3, (1,0) is the stable point of the two-player game. From the recycler's point of view, when $C_R < K$,as the recycler improves the reuse level, the subsidy from the manufacturer is greater than the cost, so the recycler will choose to improve the reuse level. From the manufacturer's point of view, $C_M > K$, the cost paid by the manufacturer is less than the subsidy obtained, so the manufacturer will not choose to improve the reuse level. Therefore, the final stable result is (improving the level of reuse and maintaining the status quo). With the continuous expansion of the market, many products will be recycled. Currently, recyclers have an advantage over manufacturers in recycling because they are closer to consumers. Therefore, recyclers will take the lead in adopting a recycling strategy to ensure a larger recycling volume. At the same time, manufacturers will not recycle because of the limited benefits of recycling.

(4) For situation 4, (1,1) is the stable point of the two-player game, and the final stable result of the system is (improving the reuse level, improving the reuse level). Under this parameter, the cost paid by recyclers and manufacturers to improve the reuse level is less than the income obtained, and recyclers and manufacturers will eventually choose to improve the reuse level. When the recycling market develops to a certain scale and maturity, both recyclers and manufacturers have a certain market share and establish a good corporate image and advanced recycling technology, so participating in recycling can create more profits for them than before. In this case, recyclers and manufacturers will choose recycling to form a competitive recycling situation.

4.3 Numerical simulation analysis of the evolution of recycler-manufacturer

This section sets different parameters to verify the conclusion. It simulates the model using Matlab 2016a software. These parameters are only set to test the rationality and feasibility of the conclusion and have no practical significance.

(1) The influence of the total cost ratio generated by the cooperation between recyclers and manufacturers on the strategy evolution.

Assuming that the parameters in the evolutionary game model of recycler and manufacturer are:

$\beta = 0.1, S = 3, C_R = 0.2, C = 0.5, K = 0.2, C_M = 0.2$,

when $\alpha = 0.1, \alpha = 0.25, \alpha = 0.5, \alpha = 0.75$, the evolution process between the probability of recyclers and manufacturers participating p and α in manufacturer cooperation is shown in Fig. 3. The influence of the total cost generated by the cooperation (a), of the total income generated by the cooperation (b), of the total income generated by the cooperation (c), of cooperation (d), of the cost generated by the recycler's choice of "improving the reuse level" (e), of compensation paid by uncooperative party to cooperative party (f) between recyclers and manufacturers on the evolution of strategy.

As seen from the above figure, when other parameters are constant, the greater the cost of recyclers, the smaller the probability of cooperation between recyclers and manufacturers.

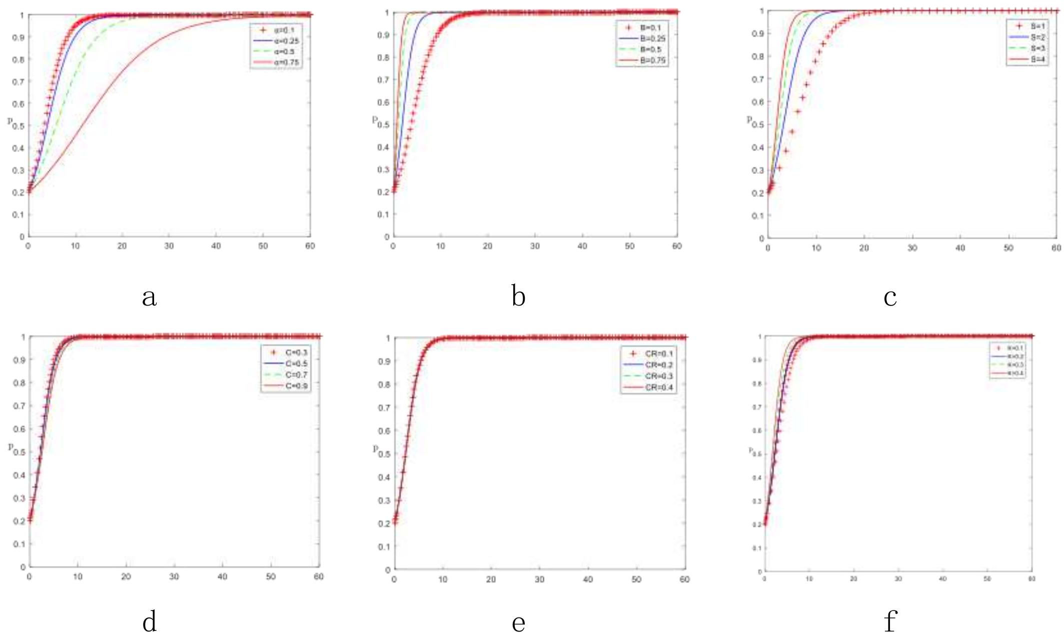

Fig. 3. Numerical simulation diagram of recycler-manufacturer evolution

(2) The influence of the proportion of extra income generated by the cooperation between recyclers and manufacturers on the strategy evolution.

Assuming that parameters in the evolutionary game model of recycler and manufacturer are: $\alpha = 0.2, S = 3, C_R = 0.2, C = 0.5, K = 0.2, C_M = 0.2$, when $\beta = 0.1, \beta = 0.25, \beta = 0.5, \beta = 0.75$, the evolution process between the probability of cooperation between recyclers and manufacturers is shown in Fig. 3(b).

When other parameters are constant, the greater the proportion of extra income generated by the participation of recyclers and manufacturers, the greater the probability of cooperation between recyclers and manufacturers.

(3) The cooperation between recyclers and manufacturers influences strategy evolution.

Assuming that the parameters in the evolutionary game model of recycler and manufacturer are: $\beta = 0.1, \alpha = 0.2, C_R = 0.2, C = 0.5, K = 0.2, C_M = 0.2$, when $S = 1, S = 2, S = 3, S = 4$, the evolution process between the probability of cooperation between recyclers and manufacturers is shown in Fig 3(c).

When other parameters are constant, the more income generated by the cooperation between recyclers and manufacturers S, the greater the probability of cooperation between recyclers and manufacturers.

(4) The total cost generated by the cooperation between recyclers and manufacturers influences strategy evolution.

Assuming that the parameters in the evolutionary game model of recycler and manufacturer are: $\beta = 0.1, \alpha = 0.2, C_R = 0.2, S = 3, K = 0.2, C_M = 0.2$, when $C = 0.3, C = 0.5, C = 0.7, C = 0.9$, The evolution process between the probability of cooperation between recyclers and manufacturers is shown in Fig 3(d).

As seen from the above figure, when other parameters are constant, the more the total cost generated by the cooperation between recyclers and manufacturers, the smaller the probability of cooperation between recyclers and manufacturers.

(5) The influence of the cost of the strategy that recyclers choose to improve the "reuse level" on the strategy evolution.

Assuming that the parameters in the evolutionary game model of recycler and manufacturer are: $\beta = 0.1, \alpha = 0.2, C = 0.5, S = 3, K = 0.2, C_M = 0.2$, when $C_R = 0.1, C_R = 0.2, C_R = 0.3, C_R = 0.4$, the evolution process between the probability of recyclers participating in cooperation is shown in Fig 3(e).

As seen from the above figure, when other parameters are constant, the cost generated by the recycler's choice to improve the "reuse level" strategy has little effect on whether the recycler and the manufacturer cooperate.

(6) The influence of the compensation paid by the uncooperative party to the cooperative party on the strategy evolution.

Assuming that the parameters in the evolutionary game model of recycler and manufacturer are: $\beta = 0.1, \alpha = 0.2, C_R = 0.2, C = 0.5, S = 3, K = 0.2, C_M = 0.2$, when $K = 0.1, K = 0.2, K = 0.3, K = 0.4$ The evolution process between the probability of recyclers participating in cooperation is shown in Fig. 3(f).

As seen from Fig. 3(f), when other parameters are constant, the compensation paid by the uncooperative party to the cooperative party has little influence.

5. Evolutionary game model among government, recyclers and manufacturers

5.1 Assumptions and parameters

According to the two-party game model, if the return on investment of recyclers and manufacturers is low, or even the income is less than the subsidy, at this time, recyclers and manufacturers in the RSC will choose not to recycle. In this case, if we want to improve the recovery rate of products, we must subsidize recyclers and manufacturers through the influence of the government to expand the scale of recycling, and reduce environmental pollution. For the RSC, the subsidy input of node enterprises has a positive externality effect, and the government encourages enterprises to strengthen the subsidy input in the RSC with subsidies.

The external macro-environment influences the subsidy input of RSC, so to reduce the cost of recycling and remanufacturing, the government can encourage enterprises to increase the subsidy input to consumers through tax reduction, exemption policies and direct subsidies.

The main players of the evolutionary game under government subsidies are still manufacturers and recyclers, and they are all bound and rational. They learn from the continuous game and change their strategic choices according to their opponents' plans to adapt to environmental changes. At the same time, before each decision, they still determine their opponents' choices. They can only estimate the possible plans of the other side of the game according to the existing information.

The following assumptions are made based on the three-parties evolutionary:

Hypothesis 1: The participants in the RSC only include the government, manufacturers and recyclers, in which the government's strategy choice is incentive or non-incentive; The manufacturer's strategy choice is to improve the treatment level or maintain the status quo; The strategy choice of recyclers is to improve the reuse level or maintain the status quo.

Hypothesis 2: The government, manufacturers and recyclers are all bounded rational economic men, and their information is not completely symmetrical to maximize profits.

Hypothesis 3: The environmental tax is only effective under the government's encouragement, and the environmental benefits brought by improving the recycling level are counted in the income function of the government subject.

Table 3 is the parameter compliance and explanation:

Table 3 Parameter Compliance and Explanation

Parameter symbol	Explanation
Government	
G_1	The cost of environmental remediation caused by the government's non-incentive measures
G_2	The benefits obtained by the government when it takes incentive measures.
G_3	Costs incurred when the government takes incentive measures.
C_{RC}	When the recycler chooses "maintaining the status quo", the government is responsible for the treatment costs generated by environmental governance.
C_{MC}	When the manufacturer chooses "maintaining the status quo", the government is responsible for the treatment cost generated by environmental governance.
G_{RR}	Environmental benefits when recyclers choose the strategy of "improving reuse level"
G_{MR}	Environmental benefits when manufacturers choose the strategy of "improving reuse level"
Recycler	
R_F	The environmental improvement payment paid to the government by recyclers when they choose the strategy of "maintaining the status quo"
R_T	Environmental tax paid by recyclers to the government when they choose the strategy of "maintaining the status quo"
S_R	Incentive subsidies are given by the government when recyclers choose the strategy of "improving treatment level"
R_C	Costs incurred by recyclers when they choose the strategy of "improving treatment level"

R_{E1}	Initial market income before recyclers cooperate.
R_{E2}	After the two parties cooperate, the recycler obtains additional market income.
Manufacturer	
M_F	Fines paid by manufacturers to the government when they choose the strategy of "maintaining the status quo"
M_T	Environmental taxes paid by manufacturers to the government when they choose the strategy of "maintaining the status quo"
S_M	Incentive subsidies are given by the government when manufacturers choose the "improving treatment level" strategy.
M_C	Costs incurred by manufacturers when they choose the strategy of "improving processing level"
M_{E1}	Initial market earnings before manufacturers cooperate.
M_{E2}	Additional market gains obtained by the manufacturer after the cooperation between the two parties.

Assuming that the probability of the government choosing the "incentive" strategy is x, the probability of choosing the "non-incentive" strategy is $1-x$; The probability that the recycler chooses the strategy of "improving the treatment level" is y, and the probability of choosing the strategy of "maintaining the status" is $1-y$; The probability that the manufacturer chooses the strategy of "improving the reuse level" is z, and the probability that the manufacturer chooses the strategy of "maintaining the status" is $1-z$, where $0 \le x, y, z \le 1$. There are eight combinations of tripartite games as follows: (1,1,1), (1,0,1), (1,1,0), (1,0,0), (0,1,1), (0,1,0), (0,0,1). The “0” means “don't encourage”, the “1” means “improve the treatment level.

5.2 Stability Analysis of Equilibrium Solution of Evolutionary Game Model

5.2.1 The solution of government evolutionary stability strategy

According to Fig. 5, the government's evolutionary stability strategy under different conditions can be discussed. In Fig. 5, the shaded part is taken as the dividing line, and the volume of area I represents the probability that the government chooses to "improve the reuse level", and the volume of area II represents the probability that the government chooses to "not improve the reuse level".

As shown in Fig. 5(a), if $(yz-y)C_{MC}-zS_M-yS_R+G_2-G_3+G_1=0$ so $F(x)=0$, the value for the government does not influence the evolution results.

As shown in Fig. 5(b), if $(yz-y)C_{MC}-zS_M-yS_R+G_2-G_3+G_1\neq 0$, when $(yz-y)C_{MC}-zS_M-yS_R+G_2-G_3+G_1<0$, and $F'(0)<0$, $F'(1)>0$ available, the evolutionary stability strategy at this time is that the government chooses the strategy of "no incentive measures"; that is $x=0$, region I in Fig 5(b).

As shown in Fig. 5 (c), if $(yz-y)C_{MC}-zS_M-yS_R+G_2-G_3+G_1\neq 0$, when $(yz-y)C_{MC}-zS_M-yS_R+G_2-G_3+G_1>0$, and $F'(0)>0$, $F'(1)<0$ available, the evolutionary stability strategy at this time is that the government chooses the strategy of "taking incentive measures". That is $x=1$, it falls in region II of the Fig 5.

It can be seen that the probability that the government "takes incentive measures" increases with the probability that manufacturers "improve the recycling level". In the same way, it can be proved that x it increases with the increase of the probability of "improving the reuse level" of recyclers y.

5.2.2 Solving the evolutionary stability strategy of the payback quotient

According to Fig. 4, the evolutionary stability strategy of the recycler under different conditions can be discussed. In Fig. 4, the shaded part is taken as the dividing line, and the volume of area I indicates the probability that the recycler chooses to "improve the reuse level", and the volume of area II indicates the probability that the recycler chooses to "not improve the reuse level".

As shown in Fig. 4(d), if $x(1-z)S_R + zR_{E2} - R_C + R_F + R_T = 0$ the value for recyclers y does not influence the evolution results.

As shown in Fig. 4(d), if $x(1-z)S_R + zR_{E2} - R_C + R_F + R_T \neq 0$, when $x(1-z)S_R + zR_{E2} - R_C + R_F + R_T < 0$, and when $F'(0) < 0$, $F'(1) > 0$, the evolutionary stability strategy is $y = 0$, and the recycler chooses the strategy of "not improving the reuse level" (region I in Fig. 4(d).

As shown in Fig. 4(d), if, when $x(1-z)S_R + zR_{E2} - R_C + R_F + R_T \neq 0$, and available $F'(1) < 0$, the evolutionary stability strategy is $y = 1$, and the recycler chooses the strategy of "improving the reuse level", it falls in region II of Fig. 4(d).

The probability of recyclers "improving the reuse level" increases with the probability of the government "adopting incentive strategies". In the same way, it can be proved that it increases with the increase of the probability of "improving the reuse level" of recyclers.

5.2.3 Solving the evolutionary stability strategy of manufacturers

The evolutionary stability strategy of the manufacturer under different conditions can be discussed. In Fig. 4, the shaded part is taken as the dividing line, and the volume of area I represents the probability that the manufacturer chooses to "take incentive measures", and the volume of area II represents the probability that the manufacturer chooses to "not take incentive measures".

As shown in Fig. 4(g), if $xS_M + yM_{E2} + M_F + M_T - M_C = 0$ so $F(z) = 0$, the value for the manufacturer z does not influence the evolution result.

As shown in Fig. 4(h), if $xS_M + yM_{E2} + M_F + M_T - M_C \neq 0$, when $xS_M + yM_{E2} + M_F + M_T - M_C < 0$, the evolutionary stability strategy is $y = 0$, the manufacturer chooses the strategy of "not improving the reuse level" area I in Fig. 4(h).

As shown in Fig. 4(i), if $xS_M + yM_{E2} + M_F + M_T - M_C \neq 0$, when $xS_M + yM_{E2} + M_F + M_T - M_C > 0$, and available $F'(0) > 0$, $F'(1) < 0$ the evolutionary stability strategy at this time is that the manufacturer chooses the strategy of "improving the reuse level". That is $y = 1$, it falls in area II in Fig. 4(i).

It can be seen that the probability of manufacturers "improving the recycling level" increases with the probability of recyclers "adopting incentive strategies". In the same way, it can be proved that the probability of the government "improving the level of reuse" increases.

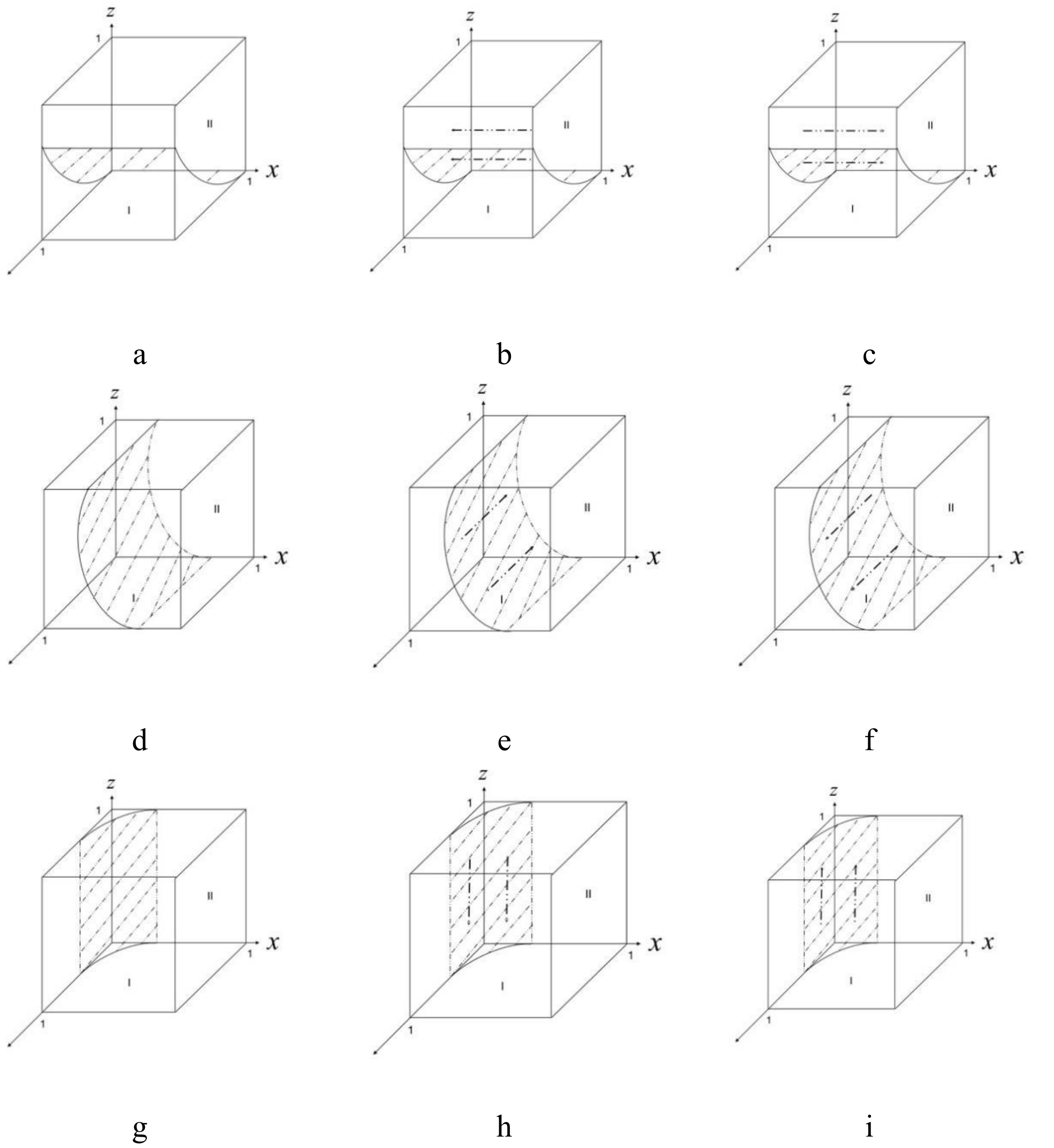

Fig. 4. Government, recycler, manufacturer's dynamic evolution phase diagram

5.2.4 Solving the stability strategy of three parties

Further, according to the analysis method of local stability proposed by Friedman and according to the two-dimensional decision equation, the differential equations about X, Y and Z are calculated, and the corresponding Jacobian matrices are listed, namely:

$$J_2 = \begin{bmatrix} J_{11} & J_{12} & J_{13} \\ J_{21} & J_{22} & J_{23} \\ J_{31} & J_{32} & J_{33} \end{bmatrix} = \begin{bmatrix} \frac{\partial F(x)}{\partial x} & \frac{\partial F(x)}{\partial y} & \frac{\partial F(x)}{\partial z} \\ \frac{\partial F(y)}{\partial x} & \frac{\partial F(y)}{\partial y} & \frac{\partial F(y)}{\partial z} \\ \frac{\partial F(z)}{\partial x} & \frac{\partial F(z)}{\partial y} & \frac{\partial F(z)}{\partial z} \end{bmatrix} \tag{7}$$

$$\begin{cases} J_{11} = (1-2x)\left[(yz-y)C_{MC} - zS_M - yS_R + G_2 - G_3 + G_1\right] \\ J_{12} = x(1-x)\left[(z-1)C_{MC}\right] \\ J_{13} = x(1-x)(zC_{MC} - S_M) \\ J_{21} = y(1-y)\left[(1-z)S_R\right] \\ J_{22} = (1-2y)\left[x(1-z)S_R + zR_{E2} - R_C + R_F + R_T\right] \\ J_{23} = y(1-y)(-xS_R + R_{E2}) \\ J_{31} = z(1-z)S_M \\ J_{32} = z(1-z)M_{E2} \\ J_{33} = (1-2z)(xS_M + yM_{E2} + M_F + M_T - M_C) \end{cases} \tag{8}$$

According to the context analysis, nine equilibrium points in the three-way evolutionary game model $T_9(x^*, y^*, z^*)$ exist under certain conditions, but there is no asymptotic stability. So, when analyzing the three-party stable equilibrium strategy, according to the Lyapunov indirect method, the stability of the two equilibrium points $T_4(0,1,1), T_8(1,1,1)$ is mainly analyzed.

Analyze the point $T_4(0,1,1)$: the Jacobian matrix under the point can be obtained according to the Eq.5. According to the analysis, when:

$-(S_M + S_R) + G_2 - G_3 + G_1 < 0$, $-R_{E2} + R_C - (R_F + R_T) < 0$, $-S_M - M_{E2} - (M_F + M_T) + M_C < 0$, $T_4(0,1,1)$ is an evolutionarily stable point. When recyclers and manufacturers take incentive measures, the incentive subsidies given by the government represent the profits obtained when the government takes incentive measures, the environmental improvement treatment fees and environmental protection taxes paid by recyclers when they choose the strategy of "maintaining the status quo", and the environmental improvement treatment fees and environmental protection taxes paid by recyclers when they choose the strategy of "maintaining the status quo".

The Jacobian matrix under the point can be obtained according to the Eq.5. According to the analysis, when $S_M + S_R - G_2 + G_3 - G_1 < 0$, $-R_{E2} + R_C - R_F - R_T < 0$, $-S_M - M_{E2} - M_F - M_T + M_C < 0$, $T_8(1,1,1)$ is an evolutionarily stable point; otherwise, the point is an unstable point or a saddle point.

5.3 Numerical Simulation of Evolutionary Game Model

In this chapter, MATLAB software will be used for numerical simulation, and the model's effectiveness will be verified based on the initial assignment. Furthermore, the influence of parameter sensitivity and initial strategy probability of each agent in the model on the evolution rate will be simulated and analyzed, and the results of evolution stability will be intuitively reflected through the simulation diagram. Finally, according to the model and simulation analysis, policy suggestions will be provided to the government, recyclers and manufacturers, respectively.

When $G_1 = 0.3, G_2 = 4, G_3 = 0.2, C_{MC} = 0.2, R_F = 1.5, R_T = 0.5, S_R = 0.1, R_C = 1.5,$ $M_F = 1.5, M_T = 0.5, S_M = 0.1, M_C = 1.5$. The evolution trend diagram is shown in Fig. 5(a). When other parameters are constant when the system evolves to a stable point, the probability of the government choosing an incentive strategy also increases when the recycler and the manufacturer cooperate to recover and generate additional income.

When $G_1 = 0.3, G_2 = 4, G_3 = 0.2, C_{MC} = 0.2, R_F = 1.5, R_T = 0.5, S_R = 0.1, R_{E2} = 2,$

$M_F = 1.5, M_T = 0.5, S_M = 0.1, M_{E2} = 2$, $R_C = 1.5, R_C = 2, R_C = 2.5, M_C = 1.5$, $M_C = 2, M_C = 2.5$.The evolution trend diagram is shown in the following Fig. 5(b). When other parameters are constant, when the system evolves to a stable point, the probability that the government will choose an incentive strategy will also decrease when the additional cost of cooperative recycling between recyclers and manufacturers increases.

When $G_1 = 0.3, G_2 = 4, G_3 = 0.2, C_{MC} = 0.2, R_F = 1.5, R_T = 0.5, R_C = 1.5, R_{E2} = 2,$ $M_F = 1.5, M_T = 0.5, M_{E2} = 2, M_C = 1.5,$ $S_R = 0.1, S_R = 0.2, S_R = 0.3, S_M = 0.1, S_M = 0.2$, $S_M = 0.3$. The evolution trend diagram is shown in the following Fig 5(c). When other parameters are constant, when the system evolves to a stable point, the probability that the government will choose an incentive strategy will also decrease when the additional cost of cooperative recycling between recyclers and manufacturers increases.

When $G_1 = 0.3, G_2 = 4, G_3 = 0.2, C_{MC} = 0.2, R_C = 1.5, R_{E2} = 2, S_R = 0.1$, $M_F = 1.5, M_T = 0.5, M_{E2} = 2, M_C = 1.5,$ and $R_F = 1.5, R_F = 2, R_F = 2.5, R_T = 0.5$, $R_T = 1, R_T = 1.5$. The evolution trend diagram is shown in the Fig. 5.

As seen from the above figure, when other parameters are constant, strengthening government punishment will reduce the recycling level's promotion to a stable point in the system evolution process.

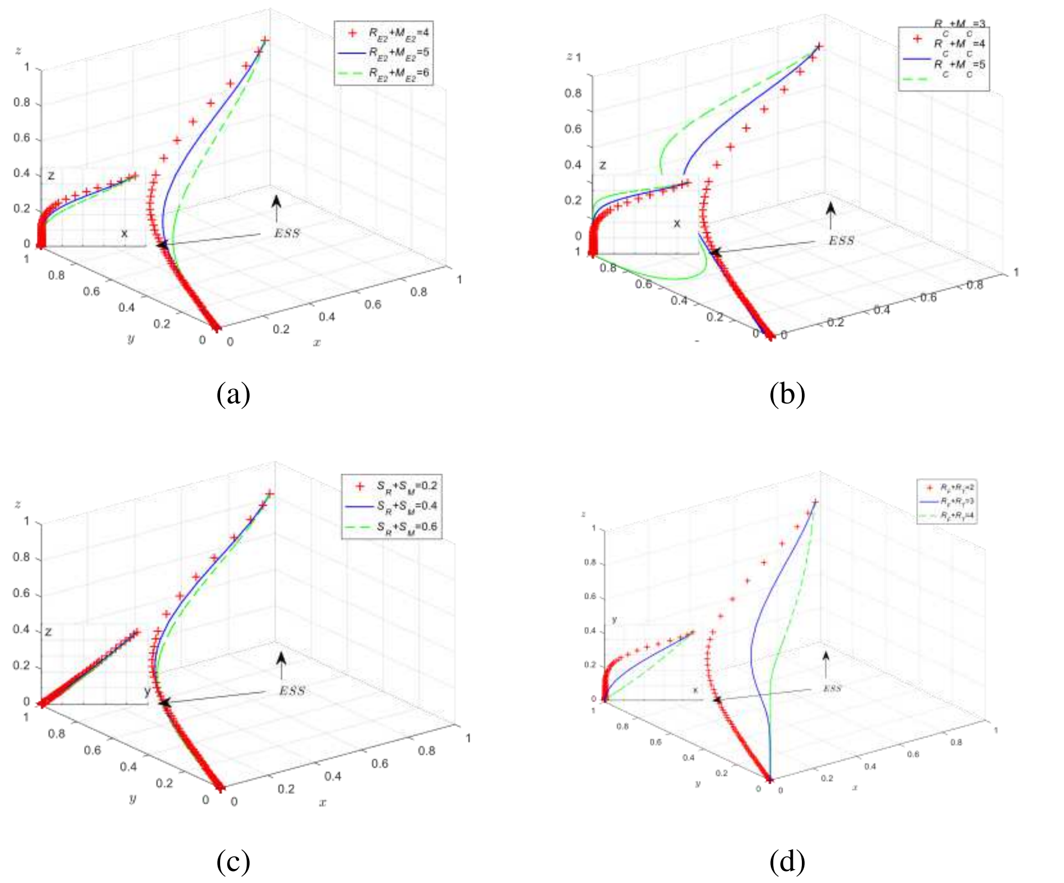

Fig. 5. Numerical simulation of evolutionary game model among government, recycler and manufacturer

6. Discussion

An evolutionary game model between vehicle manufacturers and battery recyclers of energy vehicles is developed in this paper, and the strategic stability of each player without government participation and the influence of various factors on strategic choice are analyzed. Then, the government is involved, and the influence of different government reward and punishment measures on RSC recycling is studied through evolutionary game theory. The stability of the equilibrium strategy combination of the game system, the influence of government policies on the recycling behavior of vehicle manufacturers and recyclers are obtained by comparative analysis.

In the three-way evolutionary game analysis, similar studies mostly analyze the stability of their strategies from each player's perspective but lack the overall analysis of the strategy combination in the game system. This paper analyses the stability of the equilibrium points of pure and mixed strategies of the replicated dynamic system by Lyapunov's first method. It obtains the evolutionarily stable strategy combination under different conditions.

The study of strategy selection in game theory focuses on analyzing equilibrium results. However, equilibrium results are hard to obtain reasonably, and non-equilibrium is the normal state of dynamic systems. The evolutionary game theory used in this study can analyze the evolutionary stable equilibrium of the strategic choice behavior of bounded rational subjects. The establishment of a two-way evolutionary game between vehicle manufacturers and recyclers without government participation and a three-way evolutionary game with government participation can more intuitively compare and analyze the influence of non-subsidy policy, subsidy policy, non-regulatory policy and regulatory policy on the main decisions of each subject.

The results of the proposed model in this study can be used to enhance managers' insight to make better decisions for supply chain members and government-level decision-makers. To encourage manufacturing and recycling enterprises to participate in the recycling of energy vehicles, the government can introduce macro policies and cash subsidies to reduce the costs that enterprises need to pay in the recycling process. Sharing costs for enterprises and actively promoting enterprises to participate in low-carbon recycling activities to a certain extent will help to form a recycling network quickly, mobilize the enthusiasm of enterprises to participate in recycling, and benefit consumers. On the other hand, it can gradually improve the environmental awareness of enterprises and consumers to achieve the low-carbon emission and green cycle goals.

7. Conclusion

Considering the efforts of automobile and vehicle manufacturers to recycle used batteries, respectively, the influence of government subsidies and punishment strategies on the recovery rate of used batteries is compared, analyzed and solved through numerical simulation. The results show that in the case of the game between recyclers and manufacturers, the higher the additional income of recyclers and manufacturers participating in recycling, the higher the compensation of the uncooperative party to the cooperative party, and the recyclers and manufacturers are more inclined to improve the recycling level. Compared with no subsidy and government participation, government participation can increase the recovery rate of used batteries and supply chain enterprises' profits. Theoretically, the evolutionary game theory is enriched. In the three-way evolutionary game, Lyapunov's first method is used to analyze the stability of the equilibrium point of pure strategy and mixed strategy of a replicated dynamic system. The combination of evolutionarily stable strategies under different conditions is obtained, and the combination stability of game strategies is analyzed as a whole. In practice, it is helpful for local governments to design and choose the recovery subsidy policy by comparing and analyzing the two reward and punishment measures of government subsidies and tax penalties and exploring the optimal recovery policy in different situations.

This paper assumes that only a competitive game relationship exists between automobile and vehicle manufacturers in the closed-loop supply chain. In reality, the closed-loop supply chain may pay more attention to cooperation and coordination between different enterprises to achieve the best interests together. Moreover, only the choice of recycling strategy between upstream and downstream enterprises in a closed-loop supply chain is considered, and the green consciousness of consumers is increasingly becoming a key factor that must be addressed in the success of recycling. Therefore, considering the influence of consumers' green consciousness on their purchase decisions, the profits of manufacturers and remanufacturers and even the profits of the whole closed-loop supply chain may become the research direction and focus in the next academic field.

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Authors Contributions

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Data availability Data can be made available on request.

Declarations

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Consent to participate Not applicable.

Consent for publication Not applicable.

Competing interests The authors declare no competing interests.

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