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Original Research

Game Analysis and Strategy Suggestions on Waste Sorting Management with Third-Party Supervision

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Abstract

Waste sorting management with third-party supervision is a new mode for many cities in developing countries. Based on the evolutionary game theory, this paper studies the evolutionary trends and equilibrium points of the tripartite game of waste sorting. The main research findings include: (1) the tripartite game has two possible evolutionary stability strategies; (2) the key condition for the three parties to take positive strategies is that the sum of their waste reduction reward and paying penalty is greater than their cost for waste sorting; (3) the decrease of one party's cost, the increase of its reward and penalty, the rise of recycling price and the growth of recycling quantity can promote its choice of positive strategy; (4) one party's variable changes do not only change its own strategy choice, but also adjust the strategy choice of the other two parties in the same direction; (5) the internal adjustment of waste reduction reward among three parties cannot help the three parties to choose the positive strategy. This paper is the first to study the third-party supervision issues of waste sorting using evolutionary game theory. The findings and strategy suggestions are helpful for waste sorting management.

Keywords: waste sorting management, third-party supervision, tripartite game, strategy suggests

Introduction

Waste sorting behavior is an important factor in reducing raw material usage through recycling programs and seeking circular economy implementation [1]. Originally, landfill was the main method to solve the problem of municipal waste. But with the increase of the amount of municipal waste, there are fewer and fewer suitable landfill sites close to the city. Simultaneously, the opening of long-distance landfill sites significantly increases the cost of waste transportation. Therefore, this method is being phased out step by step. In order to solve the problems caused by landfill, waste incineration has become popular. However, when the water content is high in the waste, it is difficult to improve the temperature of waste incineration, and two disadvantageous consequences are produced. On the one hand, wet waste increases the power cost of waste incineration, and on the other hand, it is easy to produce dioxins, damage the atmospheric environment

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and endanger human health. Hence, many countries began to implement waste sorting disposal methods. Waste sorting not only reduces the economic cost of waste follow-up disposal, improves the recycling rate of renewable resources, protects the natural environment in which we live, but also drives the development of related industries.

Waste sorting has been carried out in developed countries for a long time, such as Japan, Germany and Sweden. At present, it is in a relatively mature stage. However, there is no a unified model for waste sorting in the world. Each country has its emphasis according to its own national conditions. For example, cultivating citizens' awareness of conscious participation is regarded as the work core in some cities, but reward and penalty measures are highlighted in other cities. By and large, the overall development of waste sorting in the world is from extensive to fine. Germany has established a complete waste disposal industry system, with more than 250000 employees and an annual turnover of 50 billion euros, accounting for about 1.5% of the national economic output [2]. Japan has implemented waste sorting for many years and achieved remarkable results. Trillions of yen of various resources can be recovered from waste every year, such as rare earth elements most commonly used in electronic equipment. Japan can meet about 30% of its industrial demand by recycling from waste sorting. The waste sorting industry chain in Sweden is also quite developed, and the waste recycling rate is as high as 99%. Even in a famous Swedish company, the annual profit of the recycling department can reach hundreds of millions of dollars [3].

Due to the depletion of natural resources, the increase of greenhouse emissions, and the heightening of awareness for sustainable development in terms of safely reusing waste and biomass, the transformation of waste/biomass to valuable materials and energy (i.e. valorization) is emerging as a strong trend. However, for the whole world, the waste issue is still one of the most pressing challenges nowadays [4]. Two billion tons of waste are generated every year, of which only 14% is recycled, and over 37% is landfilled [5]. Around 87% of discarded textiles ended up in landfill, of which more than 90% are reusable and recyclable [6]. In developing countries, due to the lack of supervisors and other factors, it is difficult for local governments to implement all-round and effective supervision on the waste sorting activities of waste sorting operators. Therefore, local governments are interested in hiring organizations with professional environmental protection quality as a third-party to supervise waste sorting operators, which can not only alleviate the shortage of governments' supervision resources, but also meet the actual needs of supervising the safe and environmental protection production of high emission enterprises and fulfilling their environmental protection obligations. Compared with sole government supervision, the third-party supervision of waste sorting is a new management mode, which gets rid of the entanglement of interests and has higher credibility and transparency. Also be noted that, driven by economic interests, the third-party supervision organizations may neglect their duties sometimes. Therefore, when local governments encourage and entrust the third-party supervision of waste sorting, irregular government supervision must also be taken to ensure the supervision quality of the third-parties.

In the process of waste sorting, the strategy choice behaviors of the local government, third-party and operators are repeated game processes with progressive learning. The bounded rationality premise of evolutionary game theory and the reproduction mechanism of population natural selection and survival of the fittest are in line with the behavior law of the three parties. Therefore, this paper uses the evolutionary game theory to explore the behaviors and evolutionary trends under the new mode of the third-party supervision, analyze the evolutionary strategy equilibrium points of dynamic systems, and discuss the factors that have significant impacts on the results of evolutionary game. The relevant research results have important reference value for promoting waste sorting operators to carry out waste sorting, urging the third-party supervision organizations to exercise their supervision responsibilities, and encouraging local governments to strengthen the management of waste sorting.

The rest of the paper is organized as follows. The next section reviews the relevant literature. The Material and Methods section establishes an evolutionary game model and analyses the evolutionary trends and stability. The Numerical Simulation section carries out the numerical simulations of evolutionary game by using Matlab software. Then, in Results and Discussion section, the problems in application are discussed and strategy suggestions are presented. Finally, the Conclusions section summarizes the main contents and findings of the study, and also points out the limitations of the research.

Literature Review

In recent years, the problem of waste sorting has been studied by many scholars from different perspectives and theories. Referring to the literature review, the methods and tools which can promote waste sorting behavior could be distinguished as informational, social, financial and convenience [1]. Information provision is considered to be a widely used tool for encouraging pro-environmental behavior and particularly waste sorting among households [7-9]. Social norms and rules can affect the consciousness, behavior and effect of waste sorting, and disobedience to social norms can lead to penalties or social sanctions [10, 11]. The most prominent financial tool to promote waste sorting is monetary incentives which can be presented as rewards and penalties affecting an individual's behavior [12]. Convenience as a crucial factor of sorting behavior can encourage residents' participation in waste sorting activities [13].

In waste sorting research based on economic game theory, some scholars used economic factors to analyze the game results, influencing effects and strategy choices of relevant parties. Ji and Huang used a two-stage sequential strategy choice game model to analyze the economic behaviors of the main stakeholders under three different types of take-back modes, and presented that the manufacture-leading mode of reducing end-of-life waste can reach maximum social welfare and that the most efficient network system should be around the manufacturer individual take-back responsibility to build [14]. Yi, using a Stackelberg game model considering the group evolutionary characteristic, showed that the evolutionary equilibrium result of reverse supply chain is the sorting and the higher recycling price if the recovery plant obeys the oral contract of pricing by quality [15]. Ghalehkhondabi and Maihami applied Nash and Stackelberg games to study the relationship between the service price and investments in waste sorting motives, and proposed that the waste supply chain is more profitable when it is working under an integrated management structure [16]. Li and Wang suggested that introducing a unit pricing system can significantly push ahead the household waste sorting behavior for cities with relatively low initial status of environmental awareness, and immediately trigger sorting behaviors for cities with higher initial status of environmental awareness [17]. Mu and Zhang indicated that with increasing reward-penalty intensity the sorting rate and the profit of waste sorting recycling projects show upward trends while the subsidy efficiency of government decreases, and provided some suggestions on the recycling mode and the reward-penalty policy [18]. Wang et al. derived the evolutionary trends and stable strategies of the sorting and recycling governance of urban household waste using an evolutionary game model in which the local government supervision, enterprise disposal and citizen participation were incorporated, and showed that the key to promoting residents' active participation was to increase the incremental income of waste sorting, the higher negative incentives implemented by the government could restrict the enterprise operations effectively, and excessive regulatory costs can lead to management dilemmas of waste recycling [19].

Some literature on waste utilization also studied the third-party problem, but their third-party did not refer to the third-party supervision organization. For example, Liu et al. studied on recycling problems under the third-party recycling in a closed-loop supply chain [20]. Eydi proposed a model with dual-role factors and fuzzy data to select third-party reverse logistics provider [21].

However, to the best of our knowledge, no scholars have used evolutionary game theory to study the third-party supervision issues of waste sorting. Because the third-party supervision of waste sorting is a very important problem in modern urban management, this research gap needs to be filled.

Material and Methods

Main Assumptions and Variables

Evolutionary game theory, which has been applied broadly to different fields, such as economics, politics, sociology, biology, and so on [22], is also a strong tool in the study of environment protection. In the condition of information asymmetry and bounded rationality, whether each side will work positively and effectively or not becomes an evolutionary game problem.

In the waste sorting game, the players includes the waste sorting operators, the third-party supervision organization and the local government. The government purchases the services of the third-party and operators through contracts. The third-party supervises the work of the operators according to the requirements of the government, and the government also supervises the work of the third-party and operators with an uncertain probability. The variables in the game are listed in Table 1.

Payoff Matrix

In the new mode of waste sorting management, the local government irregularly supervises the behaviors of the third-party and operators, and its strategy set is {supervision, non-supervision}, in which the probabilities of its supervision and non-supervision are x and (1-x) respectively. The third-party supervises the behavior of the operators, and its strategy set is {supervision, non-supervision}, in which the probabilities of its supervision and non-supervision are y and (1-y) respectively. Driven by speculative motives, some operators may not sort waste sometimes, and their strategy set is {sorting, non-sorting}, in which the probabilities of its sorting and non-sorting are z and (1-z) respectively. Supervision and sorting are called positive strategies, while non-supervision and non-sorting are negative strategies.

Through the above analysis, the payoff matrix of the tripartite game can be obtained as shown in Table 2.

According to the payoff matrix and the actual situation of waste sorting, we can get the following views and inequalities:

- The payoff of the government is greater than 0 when the government and third-party supervise and operators sort. i.e. $Q(S_1 - S_2) - C_1 - R_2 - R_3 > 0$.
- When the government supervises and operators sort, the payoff of the third-party supervision is greater than its payoff after being fined for non-supervision. i.e. $R_2 + Q(S_2 - S_3) - C_2 > R_2 - F_{12}$.

Table 1. Variables in the game.

Stakeholders	Variables	Description
Government	S_1	Average waste reduction reward (suppose honor can be converted into money) when all parties take positive strategies
	C_1	Government's cost for supervision
Third-party	R_2	Third-party's stable revenue from contract
	C_2	Third-party's cost for supervision
	S_2	Average waste reduction reward from the government when all parties take positive strategies
	F_{12}	Government's penalty when the third-party does not supervise
Operators	R_3	Operators' stable revenue from contract
	C_{31}	The operators' fixed cost without waste sorting
	Q	Quantity of recycled materials caused by waste sorting
	p	Average selling price of recycled materials
	C_{32}	Average sorting cost of recycled materials
	S_3	Average waste reduction reward from the third-party when all parties take positive strategies
	F_{13}	Government's penalty when operators do not sort
	F_{23}	Third-party's penalty when operators do not sort

Table 2. Payoff matrix of the tripartite game.

		Operator sorting (z)	Operator non-sorting (1-z)
Government supervision (x)	Third-party supervision (y)	$Q(S_1 - S_2) - C_1 - R_2 - R_3$, $R_2 + Q(S_2 - S_3) - C_2$, $R_3 - C_{31} + Q(p + S_3 - C_{32})$	$F_{13} - C_1 - R_2 - R_3$, $R_2 - C_2 + F_{23}$, $R_3 - C_{31} - F_{13} - F_{23}$
	Third-party non-supervision (1-y)	$F_{12} - C_1 - R_2 - R_3$, $R_2 - F_{12}$, $R_3 - C_{31} + Q(p - C_{32})$	$F_{12} + F_{13} - C_1 - R_2 - R_3$, $R_2 - F_{12}$, $R_3 - C_{31} - F_{13}$
Government non-supervision (1-x)	Third-party supervision (y)	$-R_2 - R_3, R_2 - C_2$, $R_3 - C_{31} + Q(p - C_{32})$	$-R_2 - R_3, R_2 - C_2 + F_{23}$, $R_3 - C_{31} - F_{23}$
	Third-party non-supervision (1-y)	$-R_2 - R_3$, R_2, $R_3 - C_{31} + Q(p - C_{32})$	$-R_2 - R_3$, R_2, $R_3 - C_{31}$

– When all parties take positive strategies, the government's average waste reduction reward (suppose honor and reputation can be converted into money) is S_1, the third-party's average waste reduction reward received from the government is S_2, and the operators' average waste reduction reward from the third-party is S_3. Their order is $S_1 > S_2 > S_3$.
– It is assumed that at the beginning of the implementation of waste sorting, the penalty is only an inductive measure, and the amount of penalty is not too high, i.e. $F_{12} + F_{13} < C_1$ and $F_{23} < C_2$.
– The average selling price of recycled materials is less than the average sorting cost, i.e. $p < C_{32}$.
– When the government and third-party supervise, operators will be rewarded by the third-party if operators sort, and punished by the government and third-party if operators do not sort. Operators' payoff after rewarded is greater than the payoff after punished. So, $Q(p + S_3 - C_{32}) + F_{13} + F_{23} > 0$.

Dynamic Replication System

The variables U_1^y and U_1^n represent the expected return for the local government choosing the supervision and non-supervision strategies, respectively. The average expected return of the local government is U_1. Therefore,

$$U_1^y = yz(QS_1 - QS_2) + y(1-z)F_{13} + (1-y)zF_{12} + (1-y)(1-z)(F_{12}+F_{13}) - C_1 - R_2 - R_3 = -R_2 - R_3 + yzQS_1 - yzQS_2 + F_{12} - yF_{12} + F_{13} - zF_{13} - C_1$$

$$U_1^n = -R_2 - R_3$$

$$U_1 = xU_1^y + (1-x)U_1^n = -R_2 - R_3 + x(yzQS_1 - yzQS_2 + F_{12} - yF_{12} + F_{13} - zF_{13} - C_1)$$

The variables U_2^y and U_2^n represent the expected return for the third-party choosing the supervision and non-supervision strategies, respectively. The average expected return of the third-party is U_2. Therefore,

$$U_2^y = R_2 - C_2 + xzQ(S_2 - S_3) + (1-z)F_{23}$$

$$U_2^n = R_2 - xF_{12}$$

$$U_2 = yU_2^y + (1-y)U_2^n = R_2 - yC_2 + xyzQ(S_2 - S_3) + (y - yz)F_{23} - (x - xy)F_{12}$$

The variables U_3^y and U_3^n represent the expected return for the operator choosing the sorting and non-sorting strategies, respectively. The average expected return of the operator is U_3.

$$U_3^y = R_3 - C_{31} + Q(p - C_{32}) + xyQS_3$$

$$U_3^n = R_3 - C_{31} - xF_{13} - yF_{23}$$

$$U_3 = zU_3^y + (1-z)U_3^n = R_3 - C_{31} + z(Qp - QC_{32} + xyQS_3) - (1-z)(xF_{13} + yF_{23})$$

According to the evolutionary game theory, the percentage of players will grow when the fitness of those players is greater than the average fitness of the entire population, and the growth rate is represented by the differential equations in continuous time. Thus, the replicator dynamic equations are as follows:

$$F(x) = \frac{dx}{dt} = x(U_1^y - U_1) = x(1-x)(yzQS_1 - yzQS_2 + F_{12} - yF_{12} + F_{13} - zF_{13} - C_1) \quad (1)$$

$$F(y) = \frac{dy}{dt} = y(U_2^y - U_2) = y(1-y)(xzQS_2 - xzQS_3 + F_{23} - zF_{23} - C_2 + xF_{12}) \quad (2)$$

$$F(z) = \frac{dz}{dt} = z(U_3^y - U_3) = z(1-z)(Qp - QC_{32} + xyQS_3 + xF_{13} + yF_{23}) \quad (3)$$

Equations (1), (2) and (3) constitute a dynamic replication system. When the dynamic equations are equal to 0, the equilibrium points of the evolutionary game are reached. After solution, eight pure strategy equilibrium points can be obtained, which are (0, 0, 0), (1, 0, 0), (0, 1, 0), (0, 0, 1), (0, 1, 1), (1, 0, 1), (1, 1, 0), (1, 1, 1). In the parentheses, the first number represents the probability that the government chooses the supervision strategy, the second number represents the probability that the third-party chooses the supervision strategy, and the third number represents the probability that the operators choose the waste sorting strategy.

Evolutionary Stability Strategy

According to the Lyapunov Stability Theory, the system stability at certain equilibrium points can be measured by the Jacobian Matrix [23, 24]. The necessary and sufficient condition for the system to be evolutionary stable is that all the eigenvalues of the Jacobian Matrix have negative real parts. If for a certain equilibrium point, the real parts of all the eigenvalues of its corresponding Jacobian Matrix are negative, the equilibrium point is a sink point (also called an evolutionary stability strategy (ESS) point). By calculating partial derivatives of this dynamic evolutionary game system, the below Jacobian Matrix can be obtained:

$$J = \begin{bmatrix} \partial F(x)/\partial x & \partial F(x)/\partial y & \partial F(x)/\partial z \\ \partial F(y)/\partial x & \partial F(y)/\partial y & \partial F(y)/\partial z \\ \partial F(z)/\partial x & \partial F(z)/\partial y & \partial F(z)/\partial z \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{bmatrix}$$

Where

$a_{11} = (1-2x)(yzQS_1 - yzQS_2 + F_{12} - yF_{12} + F_{13} - zF_{13} - C_1)$

$a_{12} = x(1-x)(zQS_1 - zQS_2 - F_{12})$

$a_{13} = x(1-x)(yQS_1 - yQS_2 - F_{13})$

$a_{21} = y(1-y)(zQS_2 - zQS_3 + F_{12})$

$a_{22} = (1-2y)(xzQS_2 - xzQS_3 - C_2 + F_{23} - zF_{23} + xF_{12})$

$a_{23} = y(1-y)(xQS_2 - xQS_3 - F_{23})$

$a_{31} = z(1-z)(yQS_3 + F_{13})$

$a_{32} = z(1-z)(xQS_3 + F_{23})$

$a_{33} = (1-2z)(Qp - QC_{32} + xyQS_3 + xF_{13} + yF_{23})$

The eigenvalues of Jacobian Matrix at eight equilibrium points are shown in Table 3.

According to the above known inequality, E_2, E_3, E_4, E_5, E_6 and E_7 all have eigenvalues greater than 0, they are not ESS points because the condition that the equilibrium point is the ESS point is that $\lambda_1<0$, $\lambda_2<0$ and $\lambda_3<0$. The three eigenvalues of E_1 and E_8 are less than 0, so E_1 and E_8 are the two ESS points of the evolutionary game.

Numerical Simulation

In order to more intuitively show the evolutionary path of the tripartite game, the evolutionary game equilibrium can be analyzed and verified by numerical simulation using Matlab software.

ESS Point Simulation

According to the above inequality, we can set the variable values as follows: F_{12} = 12; F_{13} = 14; C_1 = 30; F_{23} = 16; C_2 = 30; Q = 20; p = 4; C_{32} = 5; S_1 = 6; S_2 = 3;

Table 3: Eigenvalues of the Jacobian matrix.

Equilibrium point	Eigenvalue	Eigenvalue	Eigenvalue
E_1 (0, 0, 0)	$F_{12}+F_{13}-C_1$	$F_{23}-C_2$	$(Qp-QC_{32})$
E_2 (1, 0, 0)	$-(F_{12}+F_{13}-C_1)$	$(F_{23}+F_{12}-C_2)$	$(Qp-QC_{32}+F_{13})$
E_3 (0, 1, 0)	$F_{13}-C_1$	$-(F_{23}-C_2)$	$(Qp-QC_{32}+F_{23})$
E_4 (0, 0, 1)	$F_{12}-C_1$	$-C_2$	$-(Qp-QC_{32})$
E_5 (0, 1, 1)	$QS_1-QS_2-C_1$	C_2	$-(Qp-QC_{32}+F_{23})$
E_6 (1, 0, 1)	$-(F_{12}-C_1)$	$(QS_2-QS_3+F_{12}-C_2)$	$-(Qp-QC_{32}+F_{13})$
E_7 (1, 1, 0)	$-(F_{13}-C_1)$	$-(F_{23}+F_{12}-C_2)$	$(Qp-QC_{32}+QS_3+F_{13}+F_{23})$
E_8 (1, 1, 1)	$-(QS_1-QS_2-C_1)$	$-(QS_2-QS_3+F_{12}-C_2)$	$-(Qp-QC_{32}+QS_3+F_{13}+F_{23})$

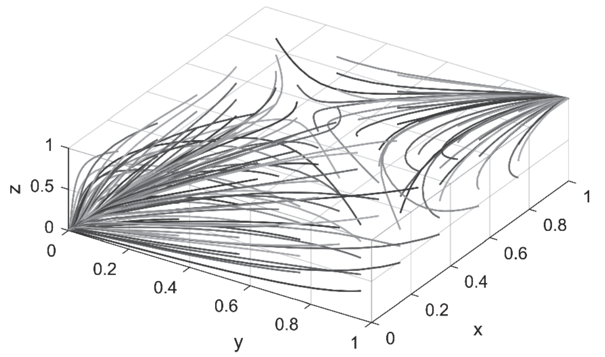

Fig. 1. Evolutionary path of tripartite game at the ESS points (0, 0, 0) and (1, 1, 1).

S_3 = 1. The evolutionary path and result are shown in Fig. 1, and the ESS points are (0, 0, 0) and (1, 1, 1).

So, we have

- Proposition 1: when the penalty income of the government and third-party cannot offset the cost of their supervision and the selling price of recycled materials is lower than their recycling cost, E1 (0, 0, 0) is an ESS point.
- Proposition 2: For the government, if its net waste reduction reward is greater than its supervision cost; for the third-party, if the sum of its net waste reduction reward and the penalty paid for non-supervision is greater than its supervision cost; for operators, if the sum of its waste reduction reward, sales income of recycled materials and the penalty paid for non-sorting is greater than their sorting cost, then E8 (1, 1, 1) is an ESS point.

Effect Simulation of Variable Change

Because the local government, the third-party and operators are rational economic men, they will make corresponding decisions according to the comparative relationship between gains and losses. By changing the value of each variable, we can observe these variables' impact on the evolutionary path of the tripartite strategy choices. In the following figures, solid line, dot dash line and dot line represent the strategy choices of the local government, the third-party and operators, respectively. The horizontal axis represents the evolutionary period (t = [0, 2]), the vertical axis represents the probability of the three parties choosing the positive strategy, and

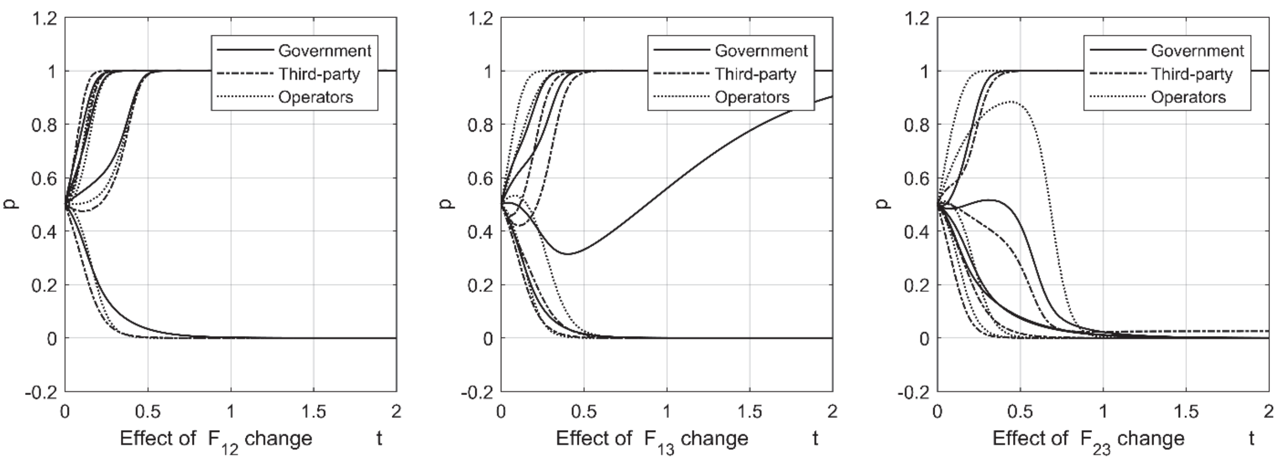

Fig. 2. Impact of penalty on the evolutionary path of tripartite strategies.

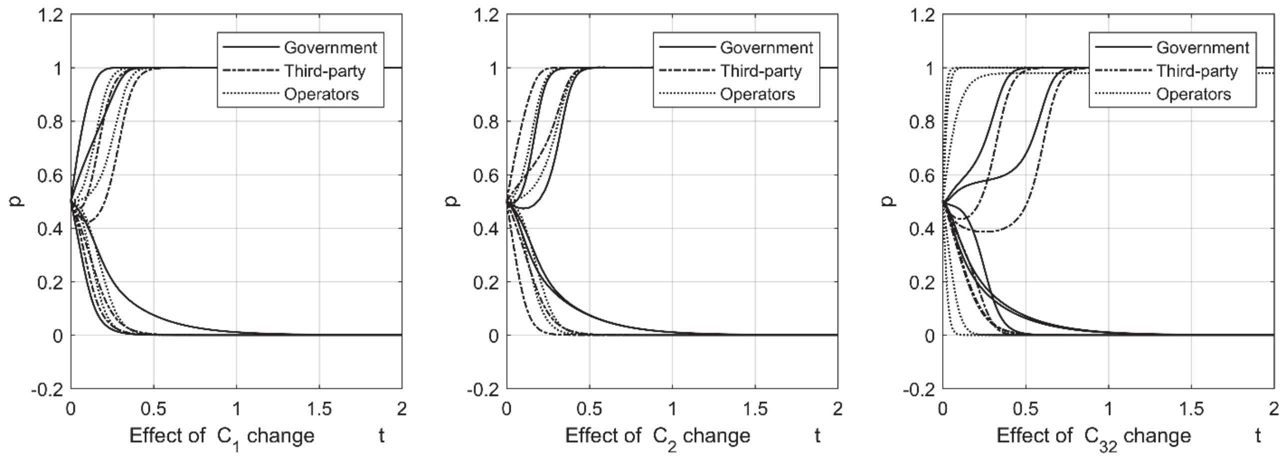

Fig. 3. Impact of cost on the evolutionary path of tripartite strategies.

the initial probabilities of the three parties choosing the positive strategy are set to 0.5.

Fig. 2 shows the impact of penalty on the evolutionary path of the tripartite game, in which F_{12}, F_{13} and F_{23} change from 10 to 40 in steps of 10. When F_{12}, F_{13} and F_{23} equal 10, the tripartite choice converges to 0, and when they increase to 40, the choice converges to 1. Simultaneously, their changes also have a same direction effect on the choice of other parties. For example, the change of F_{12} not only affects the choice of the government and the third-party, but also causes operators' choice to change in the same direction.

So, we have

– Proposition 3: the increase of penalty on one party can not only promote its choice of positive strategy, but also cause other parties' choice change in the same direction.

Fig. 3 shows the impact of cost on the evolutionary path of the tripartite game, in which C_1 and C_2 change from 10 to 40 in steps of 10, and C_{32} changes from 0 to 8 in steps of 2. When C_1, C_2 and C_{32} equal to their minimum value, the strategy choice of their own party converges to 1, and with their increase, that gradually converges to 0. Simultaneously, their changes also have a same direction effect on the strategy choices of other parties, although the response of other parties is relatively slow.

So, we have

– Proposition 4: the cost decrease of one party can not only promote its choice of positive strategy, but also cause other parties' choice change in the same direction. But the response of other parties is relatively slow.

Fig. 4 shows the evolutionary trend of tripartite strategy choice when two of variables S_1, S_2 and S_3 remain unchanged and the other variable changes within a reasonable range. The left chart of Fig. 4 shows the impact of S_1 on the evolutionary path of the tripartite game, in which $S_2 = 3$, $S_3 = 1$ and S_1 changes from 3 to 9 in steps of 2. When S_1 is equal to 3, 5 or 7, the tripartite choice is negative strategy, but when S_1 is equal to 9, the tripartite choice is positive strategy. The middle chart of Fig. 4 shows the impact of S_2 on the evolutionary path of the tripartite game, in which $S_1 = 6$, $S_3 = 1$ and S_2 changes from 1 to 6 in steps of 1. Under the condition that S_2 takes six different values, the tripartite choice is always negative strategy. The right chart of Fig. 4 shows the impact of S_3 on the evolutionary path of the tripartite game, in which $S_1 = 6$, $S_2 = 3$ and S_3 changes from 0 to 3 in steps of 1. Under the condition that S_3 takes four different values, the tripartite choice is still negative strategy. In the left chart of Fig. 5, $S_1 = 9$, $S_3 = 1$ and S_2 changes from 1 to 9 in steps of 2. When S_2 is equal to 1, 3 or 5, the tripartite choice is negative strategy, and when S_2 reaches 7, their choice is positive strategy.

Therefore, we can draw the following conclusions:

– Proposition 5: When the total amount of reward is certain, the increase of one party's reward and the decrease of the other party's reward will make the choices of the three parties converge to the negative strategy. If the total amount of reward increases, and the increase of one party's reward does not lead to the decrease of the other party's reward, the three parties will make positive strategy choices.

The middle chart of Fig. 5 shows the impact of Q on the evolutionary path of the tripartite game, in which Q changes from 0 to 40 in steps of 10. When Q is between 0 and 30, the tripartite choice is negative strategy, and when Q reaches 40, the tripartite choice is positive strategy. Q = 30 is the threshold value for operators to make different strategy choice. At this time, they will choose positive strategies with a probability of about 0.75 and negative strategies with a probability of about 0.25. In addition, there is a crossover phenomenon in operators' curves. The reason is that the change of Q value will lead to the change of the evolutionary equilibrium state, which makes the three-party strategy choice adjust suddenly at some points, and leads to the shape change of the curves.

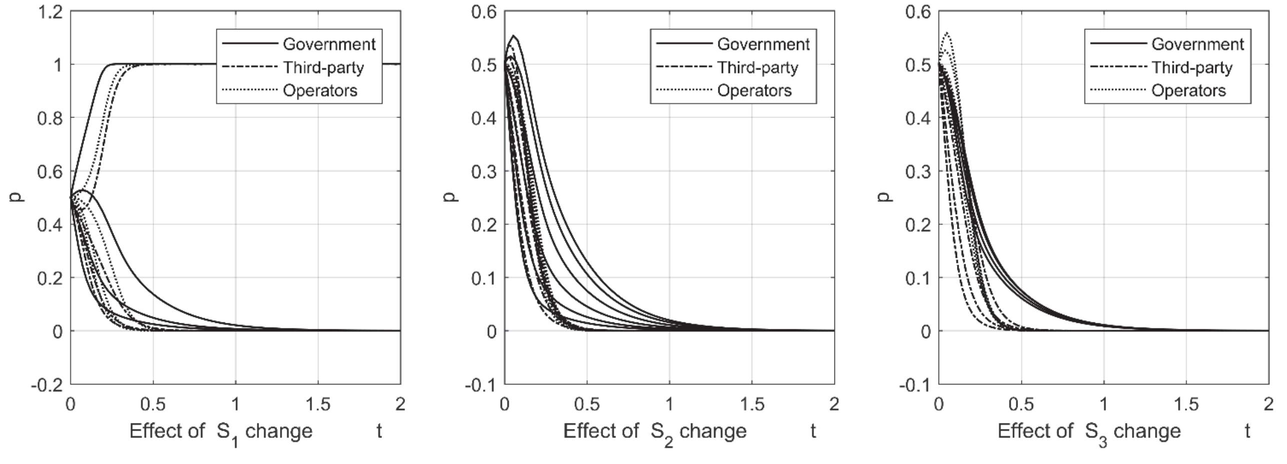

Fig. 4. Impact of reward on the evolutionary path of tripartite strategies.

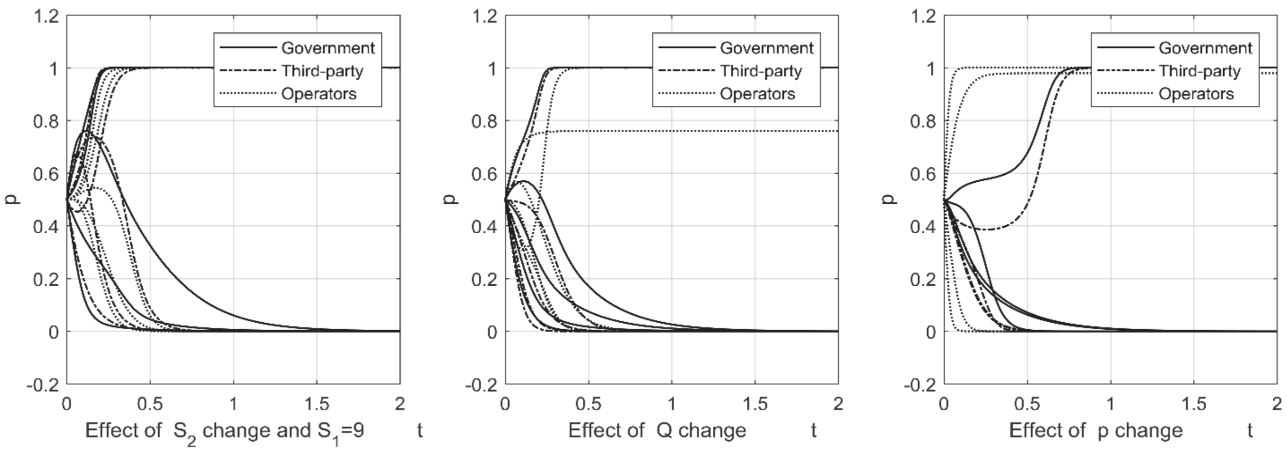

Fig. 5. Impact of penalty coefficient on the evolutionary path of tripartite strategies.

So, we have

– Proposition 6: The recycling quantity has an important impact on the strategy choice of the three parties. The government and the third-party are more sensitive to the change of recycling quantity than operators. When the recycling quantity is low, the three parties choose negative strategies. With the increase of the recycling quantity, the three parties will gradually tend to choose positive strategies.

The right chart of Fig. 5 shows the impact of p on the evolutionary path of the tripartite game, in which p changes from 1 to 7 in steps of 2. When p is equal to 1, 3 or 5, the choice of the government and the third-party is negative strategy, and only p = 7 they choose positive strategy. When p is equal to 1 or 3, operators choose negative strategy, and when p is equal to 5 or 7, operators choose positive strategy. It can be seen from the chart that operators are more sensitive to p change than the government and the third-party. So, we have

– Proposition 7: The change of recycling price has an important impact on the strategy choice of operators. When recycling price is low, operators will choose negative strategies. With the increase of recycling price, operators will gradually tend to choose positive strategies. Operators' positive strategy can increase the recycling quantity, which conversely drive the government and the third-party to choose positive strategy.

Results and Discussion

From the above 7 propositions, we can draw four main conclusions: (1) There are two ESS points in the tripartite evolutionary game, i.e. (0, 0, 0) and (1, 1, 1); (2) the decrease of one party's cost, the increase of its reward and penalty, the rise of recycling price and the growth of recycling quantity can promote its choice of positive strategy; (3) one party's variable changes do not only change its own strategy choice, but also adjust the strategy choice of the other two parties in the same direction; (4) the internal adjustment of waste reduction reward among three parties cannot help the three parties to choose the positive strategy.

These conclusions have theoretical and practical guiding significance for waste sorting management.

Problems in Application

With the development of urbanization, more and more municipal utilities implement market-oriented operation, and the overall supervision workload of waste sorting management has exceeded the bearing limit of relevant government departments. Therefore, it is imperative for the local government to adopt the third-party supervision mode in waste sorting management. Compared with traditional supervision modes, the third-party supervision mode has many advantages, including efficient management, sufficient manpower, relatively rich experience and so on. The role of a third-party as "auditors" in waste sorting management can not only effectively make up for the defects that the government is difficult to fully supervise, but also extricate the government from the heavy daily supervision work.

For example, Xiamen municipality has played important roles in developing a sound solid waste management to address institutional challenges and financial constraints due to the over-generation of municipal solid waste. Through policy intervention, institutional coordination, capacities building, and public participation, the government has formed practical policies to ensure that the city's policies and institutions would promote a zero-waste approach and circular economy in the framework of resource utilization [25]. In 2018, the Chinese government proposed to supervise and assess the implementation of waste sorting in cities and accelerate the process of waste sorting. Xiamen responded to the call of the state earlier, the third-party supervision of waste sorting was carried out smoothly, and the effect of waste sorting was remarkable. From 2000 to 2017, the average annual growth rate of household waste in Xiamen exceeded 10%. After the implementation of waste sorting, the production of household waste in Xiamen achieved negative growth, for the first time, from 1.864 million tons in 2017 to 1.83 million tons in 2018, and the harmless treatment rate of household waste reached 100%. Waste incineration power generation increased from 351 degrees per ton before sorting to 385 degrees per ton after sorting. In 2020, more than ten provinces in China launched third-party supervision projects for waste sorting, including 16 projects in Shanghai city, 10 projects in Zhejiang province and 9 projects in Jiangsu province and so on.

The third-party supervision mode has played an important role in promoting waste sorting, but there are also some problems. For example, the professional level of third-party organizations is uneven, the assessment index system used for supervision is unscientific, the supervision is not fully in place, the waste sorting of the operators is difficult to fully comply with the requirements of the contracts and the government's supervision over third-party organizations is insufficient.

To solve these problems, some experts believe that measures should be taken from two aspects: one is strengthening assessment, reward and penalty and the other is controlling tripartite costs and increasing the recycling price, which is consistent with the main conclusions derived from the above tripartite game model and the numerical simulation.

Strategy Suggestions

Strengthening Assessment, Reward and Penalty

In developing countries, the third-party supervision is a new mode of waste sorting management, and the third-party supervision organizations are also derived from other organizations. Therefore, the third-party supervision mode is not mature in many cities. In the implementation process of this mode, we should strengthen the standardization, assessment, reward and penalty of waste sorting activities, so as to promote the sustainable development of waste sorting and resource recycling. Main suggestions include:

- Formulating and issuing third-party supervision and management measures by governments for waste sorting can clarify the overall requirements of third-party supervision and standardize the behavior of third parties.
- A standard management system built by the third parties for waste sorting supervision can not only improve their professional level, but also effectively direct and standardize the behavior of operators.
- The measures taken by governments, such as strengthening the supervision and assessment, punishing the dereliction of duty and rewarding sorting behavior, can prompt the third-party and operators to choose the positive strategy.
- Supervising the operators' facility configuration of waste sorting, delivery, collection, transportation, publicity and daily management, and organizing corresponding assessment, reward and penalty according to the result of supervision are the basic means for the third parties to perform their duties.
- When the penalty income of the government and third-party is greater than the cost of their supervision, E_1 (0, 0, 0) won't be an ESS point.
- The measure of internal adjustment of waste reduction reward is inappropriate because it cannot stimulate three parties to choose the positive strategy.

Controlling Tripartite Costs and Increasing the Recycling Price

It is a kind of market behavior that the government signs an entrusted supervision contract with a third-party and the government signs a waste sorting service contract with operators. At the same time, the third-party and operators are rational economic men who pursue profits, hence they can continuously provide services only when the cost is less than the income. In order to control their cost of waste sorting and increase their income, the following suggests are worth adopting:

- Using intelligent technology and internet of things technology to realize intelligent monitoring and real-time monitoring, which can reduce the subjectivity and time lag of human supervision [26].
- Applying advanced equipment and scientific management methods. For example, Vision Servo Sorting Robot System can significantly reduce labor input and production costs of waste sorting [27]. Optimizing waste collection vehicle routing management can effectively improve work efficiency [28].
- Strengthening the knowledge publicity of waste sorting, which can promote residents to develop good waste sorting habits and help to reduce the sorting workload of operators. Numerous studies have proved that people's waste sorting behaviors are affected by government instruments or organizational support [29, 30].
- In some cases, some waste sorting projects are operating at a loss [31]. The government should provide tax relief for the operation of third parties and operators, and provide investment, loans and subsidies for the construction of waste sorting facilities, so as to reduce the operating costs of third parties and operators.
- Recycling price has a significant impact on waste sorting. Its level not only determines whether operators have the motivation of waste sorting, but also affects the recycling quantity and waste emission reduction. At the same time, the increase of recycling quantity can promote three parties to adopt positive strategies. Hence, the government should take measures such as taxes and subsidies to manage recycling prices directly or indirectly. When the price of recycling materials is greater than operators' recycling cost, E_1 (0, 0, 0) won't be an ESS point.
- Managers should pay attention to the changes of cost and income of the three parties, because the changes of cost and income of one party not only affect his strategy choice, but also affect the strategy choice of the other two parties, and lead to the change of equilibrium state.

Conclusions

Under the background that the environmental protection awareness has been generally improved all over the world, it has become an effective method in many cities that the local government uses the third-party supervision to strengthen the management of waste sorting operators. The main purpose of this study is to analyze the key conditions of choosing positive strategies in the tripartite game of waste sorting, and provide guidance for waste sorting management from the perspective of evolutionary game theory.

This is the first time to apply evolutionary game theory to study the third-party supervision model of waste sorting. At first, this paper introduces the development of waste sorting in the world, reviews the related literature on waste sorting using game theory, and finds that the evolutionary game theory research on the supervision of waste sorting operators by the third-party organization is still blank. Then, by establishing the payoff matrix and replicator dynamic equations of the tripartite game and analyzing the eigenvalues of Jacobian matrix, the evolutionary stability strategies are acquired. Subsequently, the numerical simulation is carried out and 7 propositions are proposed. Finally, combined with the practical problems in the third-party supervision of waste sorting in Xiamen, some valuable strategy suggestions are presented.

Based on the analysis of the evolutionary stability strategies of the tripartite game model, this paper finds: (1) the tripartite game has two possible evolutionary stability strategies, i.e. (supervision, supervision, sorting) and (non-supervision, non-supervision, non-sorting); (2) the key condition for the three parties to take positive strategies is that the government's net waste reduction reward is greater than its supervision cost, the sum of the third-party's net waste reduction reward and the penalty paid for non-supervision is greater than its supervision cost, and the sum of operators' waste reduction reward, sale income of recycled materials and the penalty paid for non-sorting is greater than their sorting cost; (3) the decrease of one party's cost, the increase of its reward and penalty, the rise of recycling price and the growth of recycling quantity can promote its choice of positive strategy; (4) one party's variable changes do not only change its own strategy choice, but also adjust the strategy choice of the other two parties in the same direction; (5) the internal adjustment of waste reduction reward among three parties cannot help the three parties to choose the positive strategy.

The findings have important practical as well as research implications. The above strategic suggestions on the assessment, reward, penalty, cost and price are the specific application of the findings. The findings and the strategy suggests are helpful for waste sorting management, and valuable for environmental protection.

There are two limitations to this research. First, although combined with the practical problems of the third-party supervision of waste sorting in Xiamen, some strategy suggestions are put forward by using the evolutionary game model, their actual implementation effect has not been verified by case data because the third-party supervision is still new mode for waste sorting management. Second, it did not take into account the role of the public in the supervision and management of waste sorting activities, which can be researched by a four-party game model. Future research can be carried out in these two aspects.

Conflict of Interest

The authors declare no conflict of interest.

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