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Evolutionary game theory-based system dynamics modeling for community solid waste classification in China

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ABSTRACT

To increase the utilization rate of renewable resources, China will widely implement solid waste classification in the next few years. However, waste classification in many communities has been placed on hold. This study establishes a multi-player evolutionary game among the government, community, and residents to explore the real reasons for the implementation difficulties. The evolutionary game is simulated by adopting system dynamics to analyze the effectiveness of various strategies on the game process and game equilibrium to provide references for the government to formulate macro policies. We show that fluctuations in a static penalty scheme make formulating effective strategies difficult for the government. By contrast, a dynamic penalty scheme can effectively eliminate fluctuations. Furthermore, the optimal dynamic penalty-subsidy scheme features an ideal evolutionarily stable strategy where the optimal strategy for a community and its residents is to implement the waste classification system and obey the rules, respectively.

1. Introduction

In the last ten years, with the acceleration of urbanization in China, urban domestic solid waste has rapidly increased. From 2008 to 2019, China's domestic solid waste removed increased by 56.8%, as shown in Fig. 1. A large amount of low-value recyclables, such as waste glass, waste textiles, and waste packaging paper, was discarded (Mi et al., 2016; Tong et al., 2020). The contradiction between the increasing amount of solid waste and the limited capacity of solid waste disposal has gradually emerged. Waste classification can improve the resource utilization rate of low-value recyclables and prevent them from mixing into domestic solid waste to reduce domestic waste and disposal costs (Liu et al., 2009; Mian et al., 2017). Thus, in 2020, waste classification policies were launched in big cities such as Shanghai and Beijing. Given that the policies of different cities vary slightly, this study takes Beijing's policy as a reference. The community waste classification and disposal process in Beijing is shown in Fig. 2. China's domestic solid waste removal amount achieved negative growth after implementing the waste classification policy in 2020.

Many problems in implementing a community waste classification system have not been solved (Lang et al., 2020; Xiao et al., 2018). As the current supporting facilities for solid waste collection and disposal are not fully configured, the rate of community compliance with waste classification is low. The local government needs to invest and subsidize, resulting in a lack of government funds (Li et al., 2019; Wang et al., 2019). Furthermore, residents' ecological awareness is weak in the initial stage of waste classification. Residents cannot take the initiative to classify solid waste, which makes the community arrange for staff to supervise for a long time. Thus, the community daily operating cost of waste classification is relatively high (Zhou et al., 2019).

In terms of global developments, many developed countries have successfully established their waste classification system in most cities and rural areas. Compared with China, these countries set up special government departments and have many companies for solid waste management (Wen and Lu, 2020). For example, the waste recycling rate in Germany has reached approximately 65%. Specialized enterprises deal with domestic solid waste in various communities, extracting raw materials with production value and selling them to various industries. More than 250,000 employees are in the German waste recycling industry, with an annual turnover of 50 billion euros. Furthermore, the public will be systematically taught about waste classification from primary school to enhance their awareness of ecological and environmental protection (Schüch et al., 2016).

Given the rapid urbanization of developed countries, waste

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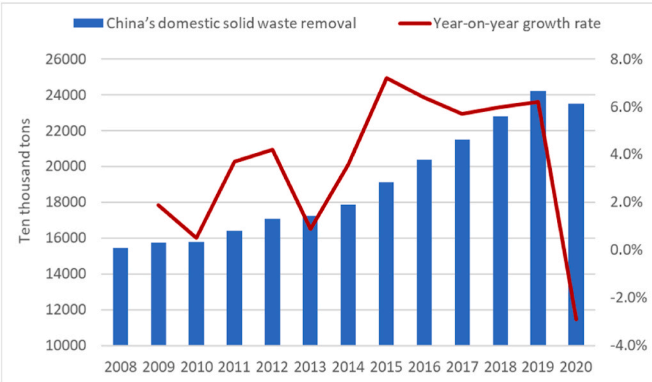

Fig. 1. Shows China's domestic solid waste removal from 2008 to 2020. *Source: China Resources and Environment Statistical Yearbook (2009–2021).*

classification has been implemented in many cities for decades. Wertz (1976) began to discuss the problem of community solid waste collection in the 1970s. Since then, more and more studies have considered the waste classification system of many developed cities in Europe and the United States. Gonzalez-Torre et al. (2003) and Smeesters et al. (1999) revealed that these related penalty and incentive policies significantly impact the implementation of waste classification. X. Liu et al. (2019) and Ye et al. (2020) proved that increasing the investment in supporting facilities and publicity will help to carry out the waste classification system quickly. Kang et al. (2020) proposed using deep learning technology to improve the efficiency of front-end waste classification. Di Vaio et al. (2019) and Grazhdani (2016) established a solid waste generation and recycling model based on the interrelationships among various influencing factors. Nainggolan et al. (2019) and Usui et al. (2017) believed that the market rules should be fully utilized. The price mechanism can effectively control the classification of solid waste and the reuse of resources. Soukopová et al. (2017) and Wang et al. (2020) identified various factors affecting residents' degree of support for waste classification. Ghalehkhondabi and Maihami (2020) employed the Stackelberg game and Nash equilibrium to analyze the relationship between the service price and investments in waste sorting motives. Furthermore, Ghalehkhondabi et al. (2020) modeled the decision-making sequence between the disposal facility and the contractor in hazardous waste management.

The progress of the waste classification implementation is considered a significant indicator to measure the urban development level, which can be evaluated in many aspects (Mi et al., 2017; Vu and Kaddoum, 2017; Zhang and Da, 2015). Ben and Zhou (2018) proposed a general framework for evaluating the implementation effects of waste classification. Demirbas (2011) studied the process of waste classification and disposal and pointed out some links on which managers should focus. Yue and Shi (2020) and Zhou et al. (2017) believed that the government should formulate policies based on the utilization and disposal of local solid waste resources. Chen et al. (2020); Zhang et al. (2017) identified the various positive effects of waste classification on the urban ecological environment. Yuan et al. (2020) pointed out that municipal solid waste treatment systems integrated with waste classification are more environmentally friendly than those with solid waste non-classification. Arı and Yılmaz (2016) and Caruso and Gattone (2019) explained that many cities must immediately improve the waste classification system. In a word, implementing a community waste classification system contributes to the sustainable development of cities.

These studies can provide a good reference for China. However, China's administrative model and urban development level are different from these countries. Wen and Lu (2020) compared and analyzed the waste classification practices of China, the US, and Germany, which

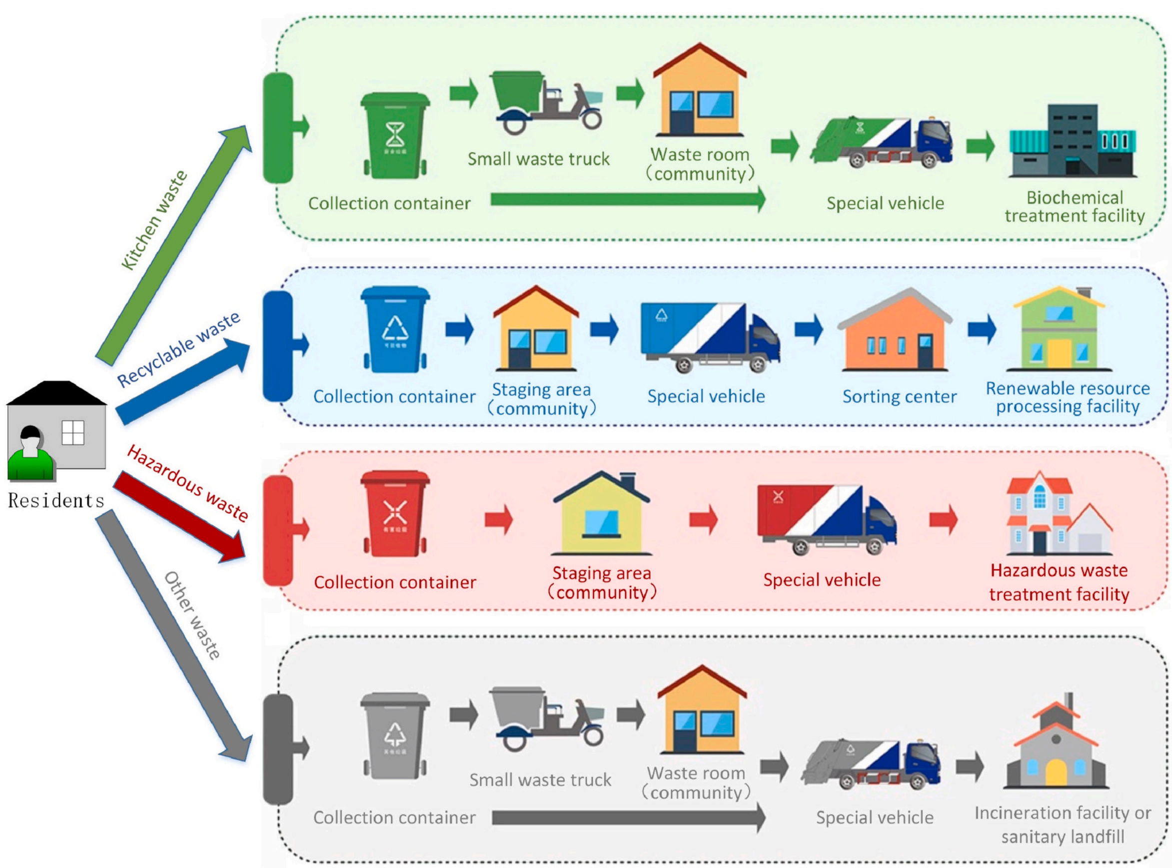

Fig. 2. Beijing's community solid waste classification and disposal process. *Source: The website of the Beijing Municipal Government.*

show differences according to their national situations. The difference is that, in China, the government plays a leading role in waste classification by enacting laws and regulations to promote implementation, and residents have not yet developed good environmental awareness. The discussion on implementing waste classification in China should be more in-depth and targeted. The present study can be extended to studies in similar countries. In the past several years, some scholars and researchers have studied the progress of waste classification in China. Wen et al. (2014) compared China's waste classification system with Europe, the US, and Japan. Shi et al. (2020) analyzed the feasibility of implementing the system in China by calculating economic profits. Cao et al. (2016) and Fan et al. (2019) proved that raising residents' ecological awareness can contribute to implementing a community waste classification system. Li et al. (2016) discussed the impact of local government policies on implementation. Ma and Zhu (2021) demonstrated that Internet use could motivate people to classify household solid waste. Jun (2017) and Xiao et al. (2020) pointed out that China currently has many shortcomings in waste recycling.

The articles mentioned above have achieved specific results in the study of waste classification, most of which are mainly based on qualitative analysis. Evolutionary game theory as a quantitative research method has been extensively applied in business management (Friedman, 1998; Hammerstein and Selten, 1994; Kandori, 1997). However, few articles use this method to discuss the problem of waste classification. Wu et al. (2021) analyzed the government and residents' behavioral strategies in household waste classification, which provided a basis for our study. Based on evolutionary game theory, the present study examines the behavior choices of the government, community, and residents in implementing the community waste classification system. It explores the impact of different schemes on the game process and the players' strategic choices. Our findings can help the government to formulate macro policies to promote the implementation of waste classification. According to the community waste classification policy issued by the Beijing Municipal Government on May 1, 2020, this study adopts system dynamics (SD) to simulate the changes and interactions of stakeholders' strategies. SD is a practical software simulation approach for analyzing feedback behavior in nonlinear high-order systems (Collins et al., 2013; Tian et al., 2014). This study adopts qualitative and quantitative methods to study China's community waste classification system and gives corresponding management suggestions.

The paper is structured as follows. Section 2 introduces the multi-player evolutionary game analysis of the community waste classification system. Section 3 presents two stability control schemes: the dynamic penalty scheme and the optimal dynamic penalty-subsidy scheme. Section 4 provides the conclusions.

2. Multi-player evolutionary game analysis of community waste classification system

The development of evolutionary game theory is to overcome traditional game theory's shortcomings in analyzing the bounded rational players and game dynamics process (Tian et al., 2019). Players' strategies must undergo an adaptive adjustment process, which is not obtained by immediate optimization calculations. In implementing the community waste classification system in China, the bounded rational players observe and compare payoffs with others to change their strategies dynamically. Evolutionary game theory is thus more appropriate for this study of the community waste classification system, making our research closer to reality.

2.1. Game design

This study simplifies the multi-player evolutionary game model by setting up the following scenarios and makes some assumptions by analyzing the implementation process of the community waste classification system in Beijing.

Assumption 1. In reality, the implementation of waste classification is a long-term process. Each player observes and compares different payoffs and dynamically changes strategies. Therefore, the government, community, and residents are all rationally bound and seek to maximize their payoffs. "Government" refers to the local government, "community" refers to the organization responsible for the operation and maintenance, and "residents" refer to the area's households. The two pure strategies that each player can choose are mutually exclusive. Players check their payoffs to determine whether to choose to adjust their strategies.

Assumption 2. Relevant parameters such as government reputation loss and ecological awareness in the community waste classification system can be quantified as positive values.

In the multi-player game process, the government chooses $\alpha(0 \leq \alpha \leq 1)$ as its strategy, where α represents the regulation rate, that is, the strength of government regulation. The larger the value of α, the stricter the government regulation. $\alpha = 1$ means that the government strictly executes its regulatory duties. Conversely, $\alpha = 0$ means the government fully neglects its regulatory duties. Although the government does not involve a large group of individuals, most governments have special departments to analyze the effects of scheme implementation and choose more beneficial strategies; thus, evolutionary game models can be used. The community chooses $\beta(0 \leq \beta \leq 1)$ as its strategy, where β represents the rate of implementing the waste classification system, that is, the degree of community waste classification implementation. $\beta = 1$ means the community implements the waste classification system. $\beta = 0$ means the community disregards the system. The residents choose $\gamma(0 \leq \gamma \leq 1)$ as its strategy, where γ represents the rate of obeying the waste classification rules, that is, the proportion of residents following the rules. $\gamma = 1$ means the residents follow government rules. $\gamma = 0$ means the residents break the rules. Fig. 3 presents the game tree model to describe the multi-player game process among the government, community, and residents. The strategy choices of the government, community, and residents are continuous.

I–VIII represent eight pure strategies in the evolutionary game model, based on which the government, community, and residents adopt mixed strategies. That is, each player decides the probability of two alternative strategies. Some additional assumptions are made based on the literature (Ben and Zhou, 2018; Liu, X. et al., 2019; Oribe-Garcia et al., 2015; Yue and Shi, 2020) to make the model more realistic.

Assumption 3. The government and community share the publicity expense for implementing waste classification. The publicity expense allocation coefficient is denoted by $a(0 \leq a \leq 1)$. If the publicity expense of the government is aP_e, the expense of the community is $(1-a)P_e$. When one party does not bear responsibility, the publicity expense P_e is solely borne by the other party.

Assumption 4. The supporting facility cost S_f for waste classification is shared by the government and community. The supporting facility cost allocation coefficient is denoted by $b(0 \leq b \leq 1)$. If the cost of the government is bS_f, the cost of the community is $(1-b)S_f$. When one party does not bear its responsibility, the supporting facility cost S_f is borne solely by the other party.

Assumption 5. The publicity expense P_e is positively correlated with the residents' ecological awareness E_c. The supporting facility cost S_f is positively correlated with the national ecological benefit E_r. The supporting facility cost S_f is positively correlated with the classified recycling economic benefit C_r.

According to the game analysis and assumptions, Table 1 shows all the parameters in the evolutionary game model of implementing the community waste classification system in China. Furthermore, Tables 2 and 3 present the payoff matrix among the government, community, and residents.

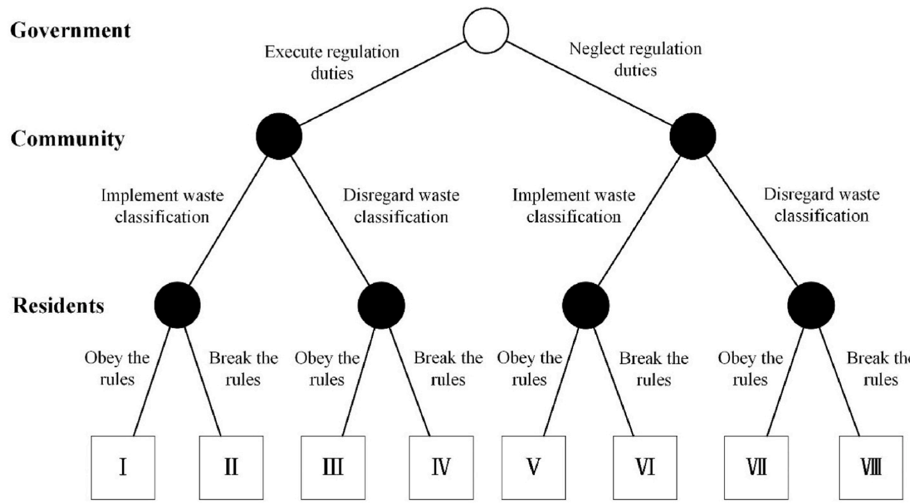

Fig. 3. Game tree model of implementing the community solid waste classification system.

Table 1
The parameters in the multi-player game model among the government, community, and residents.

Parameters	Meaning
α	Regulation rate
β	Implementation rate
γ	Obedience rate
S_c	Inspection Cost. The cost is for the government to inspect the implementation of the community waste classification system.
R_l	Government reputation loss. When the government neglects its regulation duties, the reputation of the government will be lost because of the failure to implement waste classification.
E_r	National ecological benefit. After implementing the waste classification system, some environmental benefits will be obtained.
P_e	Publicity expense. In implementing the waste classification system, the government and community must spend to publicize it to the residents.
S_f	Supporting facility cost. The government and community should cover the cost of supporting facilities to implement the waste classification system.
a	Publicity expense allocation coefficient. If the publicity expense of the government is aP_e, the expense of the community is $(1-a)P_e$.
b	Supporting-facility cost allocation coefficient. If the supporting facility cost of the government is bS_f, the cost of the community is $(1-b)S_f$.
O_c	Daily operating cost. The community must spend the daily operating costs when implementing the waste classification system.
C_r	Classified recycling economic benefit. The community gains economic benefits by implementing the waste classification system.
F_c	Fine on the community. When the community disregards the waste classification system, a fine will be paid after being inspected by the government.
G_s	Subsidies for the community. The government will subsidize the communities that implement the waste classification system.
E_x	Extra cost for the community. When residents break the waste classification rules, the community must pay additional fees to deal with solid waste.
T_c	Time cost of classification. Residents must spend the corresponding time cost when obeying the waste classification rules.
E_i	Economic cost of classification. When residents obey the waste classification rules, they must spend the corresponding economic cost.
F_i	Fine for residents. When residents break the waste classification rules, a fine will be paid after being investigated by the community.
E_c	Ecological awareness. Residents' understanding of waste classification in ecological protection.

2.2. Game solution

This study used U_{xy} to indicate the benefit of stakeholder x choosing strategy y, where $x=[g,c,r]$ denotes the government's, community's, and residents' strategies, respectively, and $y=1,2$ denotes the two strategies of the stakeholder. The expected benefits of each player should first be derived to analyze the game process. The expected benefits are the probability-weighted average value of the benefits. According to Tables 2 and 3, the government's expected benefits of executing its regulation duties U_{g1} can be obtained as follows:

Table 2
Payoff matrix of the government executing regulation duties (α).

Residents	Community	
	Implementing waste classification (β)	Disregarding waste classification ($1-\beta$)
Obeying the rules (γ)	$(-S_c+E_r-bS_f-aP_e-G_s,-O_c+C_r-(1-b)S_f+G_s-(1-a)P_e,-T_c-E_i)$	$(-S_c-S_f-P_e+F_c,-F_c,-T_c-E_i)$
Breaking the rules ($1-\gamma$)	$(-S_c+E_r-bS_f-aP_e-G_s,-O_c+C_r-(1-b)S_f+G_s-(1-a)P_e+F_i-E_x,-F_i-E_c)$	$(-S_c-S_f-P_e+F_c,-F_c,-E_c)$

Table 3
Payoff matrix of the government neglecting regulation duties ($1-\alpha$).

Residents	Community	
	Implementing waste classification (β)	Disregarding waste classification ($1-\beta$)
Obeying the rules (γ)	$(E_r,-O_c+C_r-S_f-P_e,-T_c-E_i)$	$(-R_l,0,-T_c-E_i)$
Breaking the rules ($1-\gamma$)	$(E_r,-O_c+C_r-S_f-P_e+F_i-E_x,;-F_i-E_c)$	$(-R_l,0,-E_c)$

$$U_{g1}=\beta\gamma\left(-S_c+E_r-bS_f-aP_e-G_s\right)+\beta(1-\gamma)\left(-S_c+E_r-bS_f-aP_e-G_s\right)$$

$$+(1-\beta)\gamma\left(-S_c-S_f-P_e+F_c\right)+(1-\beta)(1-\gamma)\left(-S_c-S_f-P_e+F_c\right)$$

$$=(1-b)\beta S_f+(1-a)\beta P_e+\beta(E_r-F_c-G_s)-S_c-S_f-P_e+F_c \tag{1}$$

The government's expected benefits of neglecting its regulation duties U_{g2} can be obtained as follows:

$$U_{g2}=\beta\gamma E_r+\beta(1-\gamma)E_r+(1-\beta)\gamma(-R_l)+(1-\beta)(1-\gamma)(-R_l)=\beta E_r+\beta R_l-R_l \tag{2}$$

Thus, the government's expected average benefit $\overline{U_g}$ is shown as follows:

$$\overline{U_g}=\alpha U_{g1}+(1-\alpha)U_{g2} \tag{3}$$

Based on the replicator dynamics (Friedman, 1991), in a group of bounded rational players, strategies with better-than-average benefits are gradually adopted by more players so that the proportion of players in the group adopting each strategy will change. The government's replicated dynamic equation $F(\alpha)$ is shown below:

$$F(\alpha)=\frac{d\alpha}{dt}=\alpha\left(U_{g1}-\overline{U_g}\right)=\alpha(1-\alpha)\left(U_{g1}-U_{g2}\right)$$

$$=\alpha(1-\alpha)\left[(1-b)\beta S_f+(1-a)\beta P_e-\beta F_c-\beta G_s-S_c-S_f-P_e+F_c-\beta R_l+R_l\right] \tag{4}$$

Similarly, from Tables 2 and 3, the community's expected benefits of implementing waste classification and disregarding waste classification, namely, U_{c1} and U_{c2}, are respectively obtained as follows:

$$\begin{aligned}U_{c1} &= \alpha\gamma\left[-O_c+C_r-(1-b)S_f+G_s-(1-a)P_e\right]+\alpha(1-\gamma)\left[-O_c+C_r-(1-b)S_f+G_s\right.\\ &\left.-(1-a)P_e+F_i-E_x\right]+(1-\alpha)\gamma\left(-O_c+C_r-S_f-P_e\right)+(1-\alpha)(1-\gamma)\left(-O_c+C_r-S_f-P_e+F_i-E_x\right)\\ &= b\alpha S_f+a\alpha P_e+\alpha G_s-O_c+C_r-S_f-P_e+F_i-E_x-\gamma F_i+\gamma E_x\end{aligned} \tag{5}$$

$$U_{c2}=\alpha\gamma(-F_c)+\alpha(1-\gamma)(-F_c)=-\alpha F_c \tag{6}$$

The community's expected average benefit $\overline{U_c}$ is shown as follows:

$$\overline{U_c}=\beta U_{c1}+(1-\beta)U_{c2} \tag{7}$$

Thus, the community's replicated dynamic equation $F(\beta)$ is shown below:

$$\begin{aligned}F\left(\beta\right) &= \frac{d\beta}{dt}=\beta\left(U_{c1}-\overline{U_c}\right)\\ &=\beta\left(1-\beta\right)\left(b\alpha S_f+a\alpha P_e+\alpha G_s-O_c+C_r-S_f-P_e+F_i-E_x\right.\\ &\quad\left.-\gamma F_i+\gamma E_x+\alpha F_c\right)\end{aligned} \tag{8}$$

Moreover, the residents' expected benefits of obeying the rules and breaking the rules, namely, U_{r1} and U_{r2} are respectively obtained as follows:

$$U_{r1}=\alpha\beta(-T_c-E_i)+\alpha(1-\beta)(-T_c-E_i)+(1-\alpha)\beta(-T_c-E_i)+(1-\alpha)(1-\beta)(-T_c-E_i)$$

$$=-T_c-E_i \tag{9}$$

$$U_{r2}=\alpha\beta(-F_i-E_c)+\alpha(1-\beta)(-E_c)+(1-\alpha)\beta(-F_i-E_c)+(1-\alpha)(1-\beta)(-E_c)$$

$$=-\beta F_i-E_c \tag{10}$$

The residents' expected average benefit $\overline{U_r}$ is as follows:

$$\overline{U_r}=\gamma U_{r1}+(1-\gamma)U_{r2} \tag{11}$$

Therefore, the residents' replicated dynamic equation $F(\gamma)$ is as follows:

$$F(\gamma)=\frac{d\gamma}{dt}=\gamma(U_{r1}-\overline{U_r})=\gamma(1-\gamma)(-T_c-E_i+\beta F_i+E_c) \tag{12}$$

To summarize, we can employ the following replicated dynamic equation set to represent the multi-player game model of implementing the community waste classification system:

$$\begin{cases}F(\alpha)=\alpha(1-\alpha)\left[(1-b)\beta S_f+(1-a)\beta P_e-\beta F_c-\beta G_s-S_c-S_f-P_e+F_c-\beta R_l+R_l\right]\\ F(\beta)=\beta(1-\beta)\left(b\alpha S_f+a\alpha P_e+\alpha G_s-O_c+C_r-S_f-P_e+F_i-E_x-\gamma F_i+\gamma E_x+\alpha F_c\right)\\ F(\gamma)=\gamma(1-\gamma)(-T_c-E_i+\beta F_i+E_c)\end{cases} \tag{13}$$

2.3. Game analysis based on system dynamics

SD is a computer simulation approach based on feedback control theory. It can establish a simulation model and deeply study the information feedback behavior in complex systems by effectively combining qualitative and quantitative analysis (Poles, 2013). The SD simulation model can objectively reveal the laws of development of things and provide managers with decision-making references (Currie et al., 2018; Ruutu et al., 2017; Sterman, 2002). The relationship between variables can be expressed by simple mathematical equations, functions, or logical relationships, allowing the use of computers to simulate the dynamics of real systems and investigate the intrinsic behavioral laws affecting them. Many studies have demonstrated that this method can be used to explore the evolutionary game process (Liu et al., 2015; Liu, Q. et al., 2019).

Based on the game analysis and assumptions, the multi-player evolutionary game SD model of implementing the community waste classification system is established using Vensim DSS v5.6a. Fig. 4 presents this SD model, which comprises three sub-systems: the government, community, and residents. The rectangles represent level variables that show the cumulative results. The valves represent the rate variables showing the physical flows of the items feeding into or depleting the model. The other variables are exogenous and auxiliary. This model includes 3 level variables, 3 rate variables, 13 exogenous variables, and 15 auxiliary variables. According to Demirbas (2011), Yue and Shi (2020), and Zhang et al. (2016), the three relationships are set as follows: national ecological benefit (E_r) = 1.82*supporting facility cost (S_f), classified recycling economic benefit (C_r) = 0.84*supporting facility cost (S_f), and ecological awareness (E_c) = 0.64*publicity expense (P_e). Moreover, setting the functional relationship between all parameters depends on the above equations (1) – (12).

According to *China Resources and Environment Statistical Yearbook*, *Community Waste classification Policy*, and other publicly available data

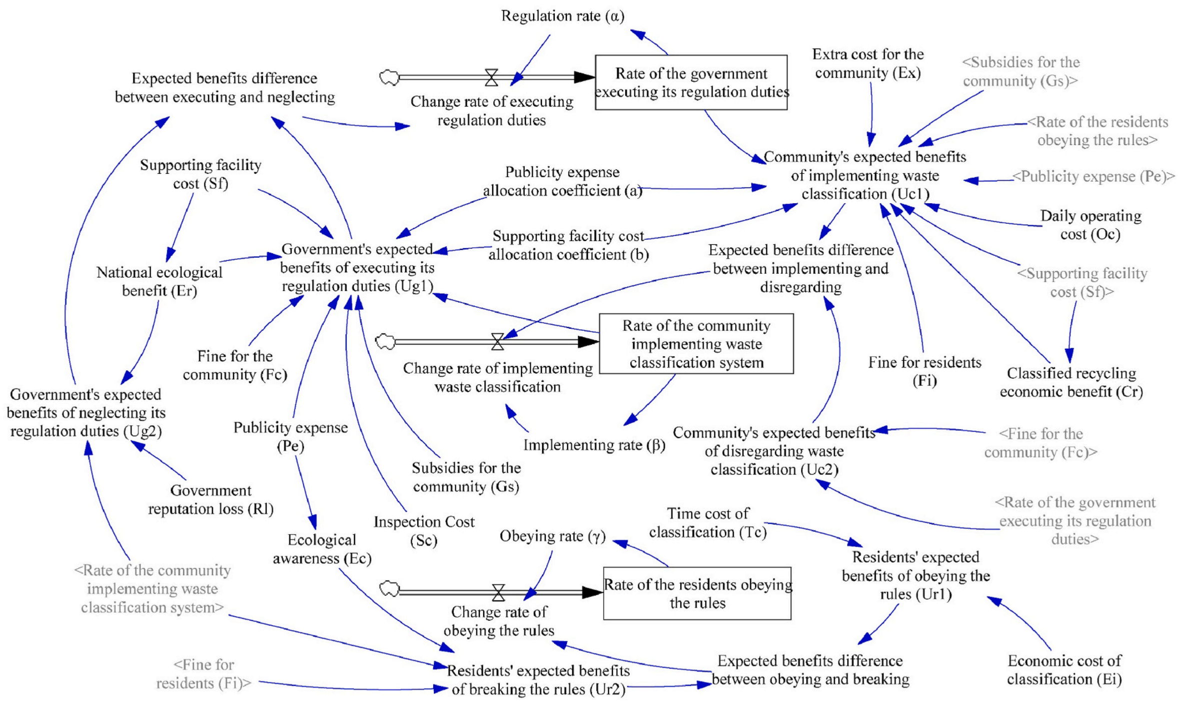

Fig. 4. Evolutionary game SD model of implementing the community waste classification system.

Table 4
The real-world values of some parameters.

Parameters	Values	Unit	Remark
a	0.42	–	Investigation
b	0.55	–	Investigation
S_c	¥8800	yuan/community/month	Investigation
R_l	¥1200	yuan/ton	Assumption
P_e	¥350000	yuan/community/year	Logical inference
S_f	¥595	yuan/ton	Institutional report
T_c	12	minute/day	Institutional report
E_i	¥98	yuan/family/year	Institutional report
F_i	¥50 – 200	yuan	Announcement
O_c	¥390	yuan/ton	Institutional report
F_c	¥20000 – 100000	yuan	Announcement
G_s	¥100	yuan/family/year	Logical inference
E_x	¥11.25	yuan/family/month	Investigation

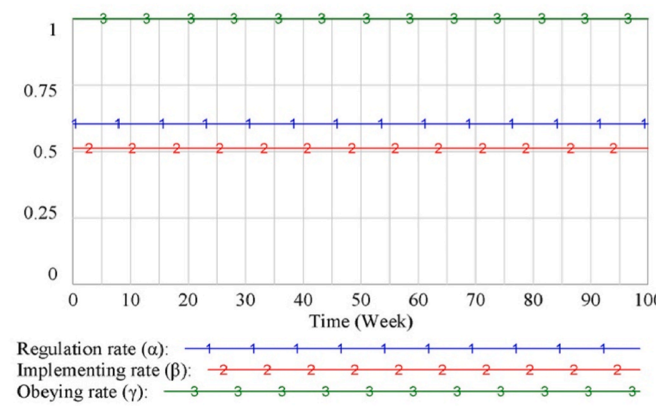

Fig. 5. Game results under initial strategy E_9

Table 5
The initial values of exogenous parameters.

Parameters	Meaning	Initial values	Notes
a	Publicity expense allocation coefficient	0.42	$0 \le a \le 1$
b	Supporting facility cost allocation coefficient	0.55	$0 \le b \le 1$
S_c	Inspection cost	3	$S_c > 0$
R_l	Government reputation loss	15	$R_l > 0$
P_e	Publicity expense	4.5	$P_e \ge 0$
S_f	Supporting facility cost	6.5	$S_f > 0$
O_c	Daily operating cost	5	$O_c > 0$
F_c	Fine for the community	10	$F_c \ge 0$
G_s	Subsidies for the community	2	$G_s \ge 0$
E_x	Extra cost for the community	3	$E_x > 0$
T_c	Time cost of classification	3	$T_c > 0$
E_i	Economic cost of classification	1	$E_i > 0$
F_i	Fine for residents	2	$F_i \ge 0$

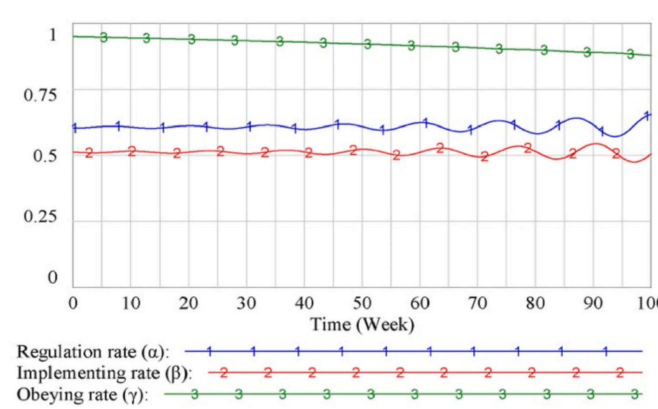

Fig. 6. Game results of existing mutation E_9 ($\gamma \rightarrow 0.95$)

sources, the real-world values of some parameters in Table 1 are shown in Table 4. The model's initial values of exogenous parameters are presented in Table 5 after pre-treatment. The basic setting of the SD model is INITIAL TIME = 0, FINAL TIME = 100, TIME STEP = 0.25, Units for Time: Week, and Integration Type: Euler.

In the equation set (13), let $F(\alpha) = F(\beta) = F(\gamma) = 0$ (i.e., the game is in equilibrium), and nine equilibrium solutions can be obtained as follows:

$$E_1 = \begin{pmatrix} 0 \\ 0 \\ 0 \end{pmatrix}, E_2 = \begin{pmatrix} 0 \\ 1 \\ 0 \end{pmatrix}, E_3 = \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix}, E_4 = \begin{pmatrix} 0 \\ 1 \\ 1 \end{pmatrix}, E_5 = \begin{pmatrix} 1 \\ 0 \\ 0 \end{pmatrix}, E_6 = \begin{pmatrix} 1 \\ 1 \\ 0 \end{pmatrix}, E_7 = \begin{pmatrix} 1 \\ 0 \\ 1 \end{pmatrix}, E_8 = \begin{pmatrix} 1 \\ 1 \\ 1 \end{pmatrix}, E_9 = \begin{pmatrix} 0.603 \\ 0.512 \\ 1 \end{pmatrix},$$

where E_1–E_8 are pure strategy equilibrium solutions and E_9 is a mixed strategy equilibrium solution.

Furthermore, E_9 is put into the above SD model, and the simulation result is presented in Fig. 5. The result shows that the government, community, and residents do not actively change their initial strategies, which is a relatively balanced state. When other equilibrium solutions E_1–E_8 are put into the SD model, the simulation results are similar to Fig. 5.

However, whether E_9 is an evolutionarily stable strategy (ESS) needs to be further checked. The stakeholder adopting ESS should be sufficient to resist a small amount of mutation (Taylor and Jonker, 1978). For example, if few residents mutate their initial strategies, obeying the rate γ change from 1 to 0.95, then the SD model simulation result is presented in Fig. 6.

The simulation results show that E_9 is not an ESS. When the initial value of the obedience rate γ is slightly changed, the relatively balanced state of E_9 is broken, and the other two stakeholders' strategy choices are in an unstable state of fluctuation. The reason is that a few residents increase their benefits after changing their initial strategies, leading to other residents starting to imitate their behavior to break the rules. In the same way, the balanced state of the eight pure strategy equilibrium solutions is checked. According to the simulation results, none of E_1–E_8 is an ESS.

A more common management solution for the government is to increase the penalties imposed on the community in guiding the implementation of waste classification. In the model in Fig. 4, adjusting the penalty strength that the government imposes on the community when it does not implement waste classification, the government's penalty on the community is changed from $F_c = 10$ to $F_c = 8$ and $F_c = 12$, and the initial strategies of the three players are set as $\alpha = 0.5$, $\beta = 0.5$, and $\gamma = 0.5$. The strategy choices of the government and the community at different penalty strengths are shown in Figs. 7 and 8.

The simulation results in Fig. 7 illustrate that the frequency and amplitude of fluctuations in the probability of government regulation during the evolutionary game increase with the strength of the penalty. Similarly, as shown in Fig. 8, the community's implementation rate increases with the enhancing strength of the penalty over the same period. However, the frequency and amplitude of the community's fluctuations during the evolutionary game also increase with the higher strength of the penalty. The reason is that when penalty strength is enhanced, the community will change its strategy quickly and more radically to limit the losses from the penalty. Then, the government will also make corresponding changes.

Therefore, only enhancing the strength of the penalty is not effective in suppressing the fluctuation of all players' strategy choices. The higher penalty imposed by the government on the community can promote implementation in the short term; as the penalty strength enhances, the implementation rate increases faster. However, the players are unable to keep this strategic choice. This management solution can only be effective in the short term, and the game remains volatile, with increasing amplitude and frequency.

In conclusion, this multi-player evolutionary game has no ESS, and the behavior of all stakeholders cannot be effectively controlled. In implementing community waste classification, even if only a small number of residents break the rules initially, more and more residents will disobey the rules as time goes by. This kind of fluctuation in the evolutionary game is not beneficial for the strategic choices of all stakeholders. Furthermore, using SD to simulate the multi-player evolutionary game among the government, community, and residents is a practical way to analyze the stability of equilibrium solutions.

3. Stability control schemes of community waste classification system

When the evolutionary game has fluctuations, the government has difficulty formulating effective regulation strategies. Therefore, stability control schemes need to be studied to eliminate these fluctuations.

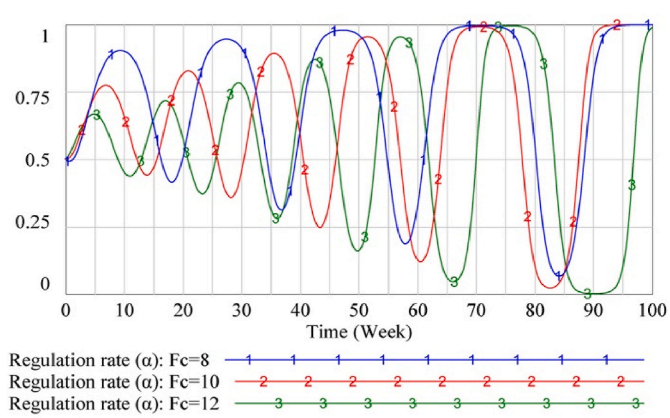

Fig. 7. Effect of different penalty strengths on government.

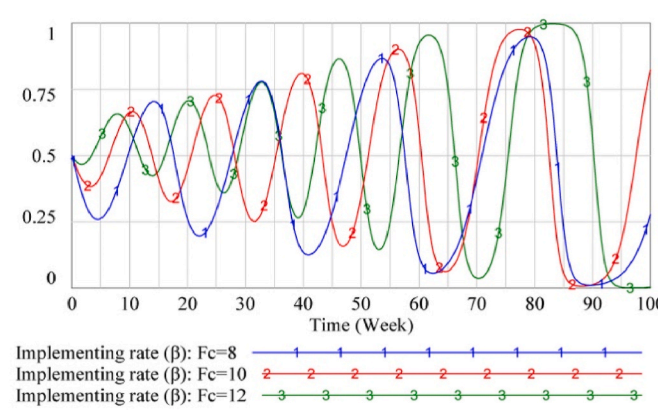

Fig. 8. Effect of different penalty strengths on community.

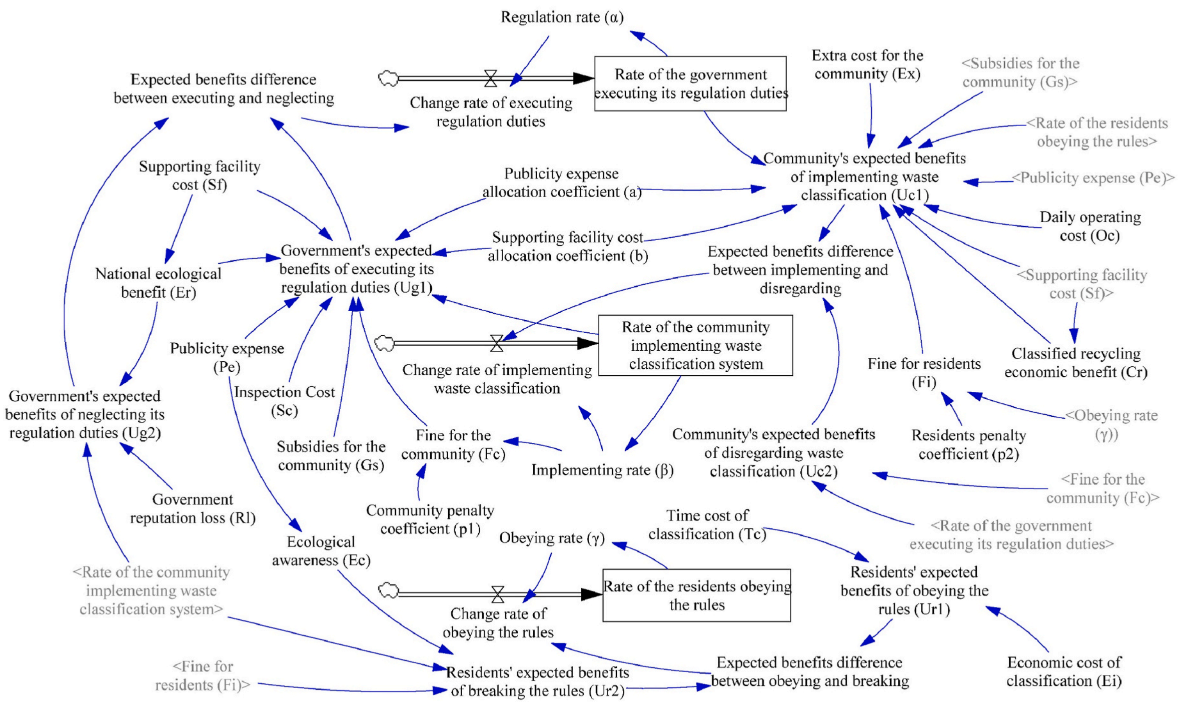

Fig. 9. Modified SD model under the dynamic penalty scheme.

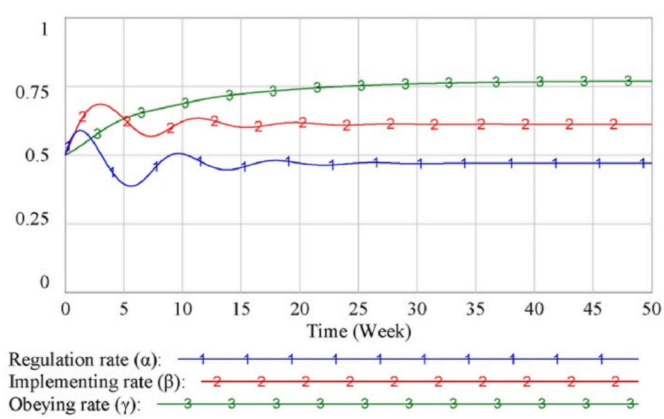

Fig. 10. Game results under dynamic penalty scheme ($\alpha = 0.5, \beta = 0.5, \gamma = 0.5$)

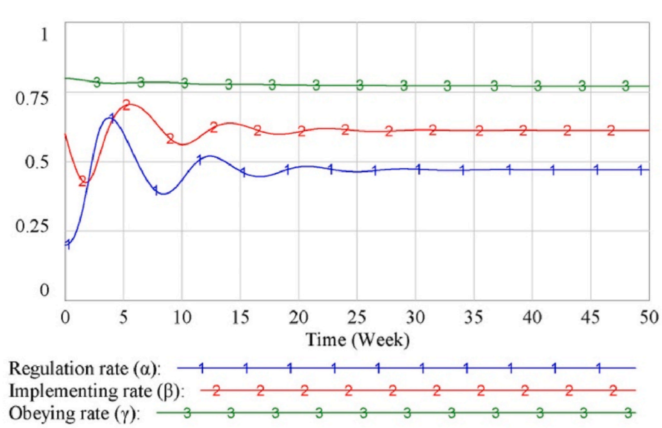

Fig. 11. Game results under dynamic penalty scheme ($\alpha = 0.2, \beta = 0.6, \gamma = 0.8$)

3.1. Stability analysis and check under the dynamic penalty scheme

To eliminate the fluctuations in the evolutionary game, many studies put forward an idea to correlate penalties with the stakeholder's unlawful behavior (Jiang et al., 2018; Liu et al., 2015, 2019; Q. Liu et al., 2019; Xie et al., 2018). Therefore, the dynamic penalty scheme is proposed to eliminate the fluctuations; that is, the government makes penalties dynamically according to the rate for the community implementing the waste classification system, and the community makes penalties dynamic according to the rate of the residents obeying the rules, as shown in the following two equations:

$$F_c^* = p_1 F_c (1-\beta), F_i^* = p_2 F_i (1-\gamma), \tag{14}$$

where p_1 and p_2 represent the penalty coefficients of the community and the residents, respectively, which are all set to 4 in the scheme. The modified multi-player evolutionary game SD model is shown in Fig. 9.

Figs. 10 and 11 show the simulation results when the initial strategies of the government, community, and residents are randomly set to $\alpha = 0.5, \beta = 0.5, \gamma = 0.5$ and $\alpha = 0.2, \beta = 0.6, \gamma = 0.8$, respectively.

In the dynamic penalty scheme, even if the initial strategies are different, the three stakeholders of the government, community, and residents play games over time and eventually stabilize at $E^*(0.470, 0.612, 0.771)$, eliminating the fluctuations in the above model. E^* is the evolutionary stable equilibrium solution.

However, the simulation results need to be further verified. First, substituting $F_c{}^*$ and $F_i{}^*$ into the equation set (13), the new replicated dynamic equation set is obtained as follows:

$$\begin{cases} F^*(\alpha) = \alpha(1-\alpha)\left(40\beta^2 - 91.465\beta + 41\right) \\ F^*(\beta) = \beta(1-\beta)\left(47.465\alpha - 13\gamma + 8\gamma^2 - 40\alpha\beta - 5.54\right) \\ F^*(\gamma) = \gamma(1-\gamma)(8\beta - 8\beta\gamma - 1.12) \end{cases} \tag{15}$$

In the replicated dynamic equation set (15), let $F^*(\alpha) = F^*(\beta) = F^*(\gamma) = 0$, and sixteen equilibrium solutions can be obtained as follows: $E_1^*(0,0,0)^T$, $E_2^*(0,1,0)^T$, $E_3^*(0,0,1)^T$, $E_4^*(0,1,1)^T$, $E_5^*(1,0,0)^T$, $E_6^*(1,1,0)^T$, $E_7^*(1,0,1)^T$, $E_8^*(1,1,1)^T$, $E_9^*(0.241, 0.612, 0)^T$, $E_{10}^*(0, 0.104, 0.351)^T$, $E_{11}^*(0,1,0.86)^T$, $E_{12}^*(0.459, 0.612, 1)^T$, $E_{13}^*(1, 0.916, 0.847)^T$, $E_{14}^*(1,1,0.86)^T$, $E_{15}^*(1, 0.923, 1)^T$, and $E_{16}^*(0.470, 0.612, 0.771)^T$, where

E_1^*–E_8^* are pure strategy equilibrium solutions and E_9^*–E_{16}^* are mixed strategy equilibrium solutions.

According to evolutionary game theory, when the real part of all the characteristic values of the Jacobian matrix evaluated from an equilibrium solution is not greater than 0, then the equilibrium solution is an ESS (Araujo and Moreira, 2014; Friedman, 1991). The Jacobian matrix of the replicated dynamic equation set (15) is shown as follows:

$$J=\begin{bmatrix}(1-2\alpha)A & \alpha(1-\alpha)(-91.465+80\beta) & 0\\ \beta(1-\beta)(47.465-40\beta) & -40\alpha\beta(1-\beta)+(1-2\beta)B & \beta(1-\beta)(-13+16\gamma)\\ 0 & \gamma(1-\gamma)(8-8\gamma) & -8\beta\gamma(1-\gamma)+(1-2\gamma)C\end{bmatrix}, \quad (16)$$

where $A=41-91.465\beta+40\beta^2, B=-5.54+47.465\alpha-40\alpha\beta-13\gamma+8\gamma^2, C=-1.12+8\beta-8\beta\gamma$.

Furthermore, $E_1^*-E_{15}^*$ are substituted into the Jacobian matrix (16) and are calculated to obtain their characteristic values. The characteristic value, which is greater than 0, appeared in each Jacobian matrix, indicating that none $E_1^*-E_{15}^*$ is the ESS of this evolutionary game. As for E_{16}^*, its Jacobian matrix $J(E_{16}^*)$ is shown as follows:

$$J\left(E_{16}^*\right)=\begin{bmatrix}0.0003108 & -10.588 & 0\\ 5.45793 & -4.63586 & -0.157671\\ 0 & 0.323456 & -0.865075\end{bmatrix} \quad (17)$$

The characteristic values of the Jacobian matrix (17) are as follows: $\lambda_1=-0.864266$, $\lambda_2=-2.31818-7.24343i$, and $\lambda_3=-2.31818+7.24343i$. Therefore, the real parts of all characteristic values are less than 0, indicating that $E_{16}^*(0.470, 0.612, 0.771)^{\mathrm{T}}$ is the ESS.

In conclusion, the dynamic penalty scheme proposed in this study effectively eliminates the fluctuations and makes the game stable. Compared with the static penalty scheme, the behavior of all stakeholders can be effectively controlled. This way, relevant departments can formulate suitable policies to implement community waste classification. Moreover, the results solved by evolutionary game theory are consistent with the simulation results. The evolutionary game process can be simulated by adopting the SD model to obtain the ESS accurately.

3.2. Stability analysis and check under the optimal dynamic penalty-subsidy scheme

For the ESS of the dynamic penalty scheme, the rate of the government executing its regulation duties is relatively high, and the rate of the community implementing a waste classification system and the rate of the residents obeying the rules are relatively low; that is, the E_{16}^* is not an ideal ESS. Although each player maximizes their own payoff, the payoff

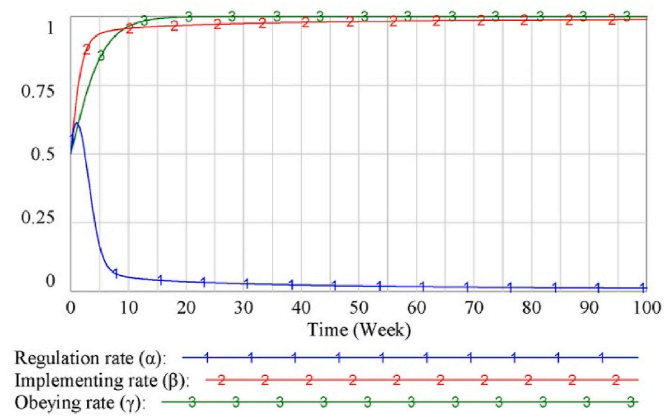

Fig. 13. Game results under the optimal dynamic penalty-subsidy scheme ($\alpha = 0.5, \beta = 0.5, \gamma = 0.5$)

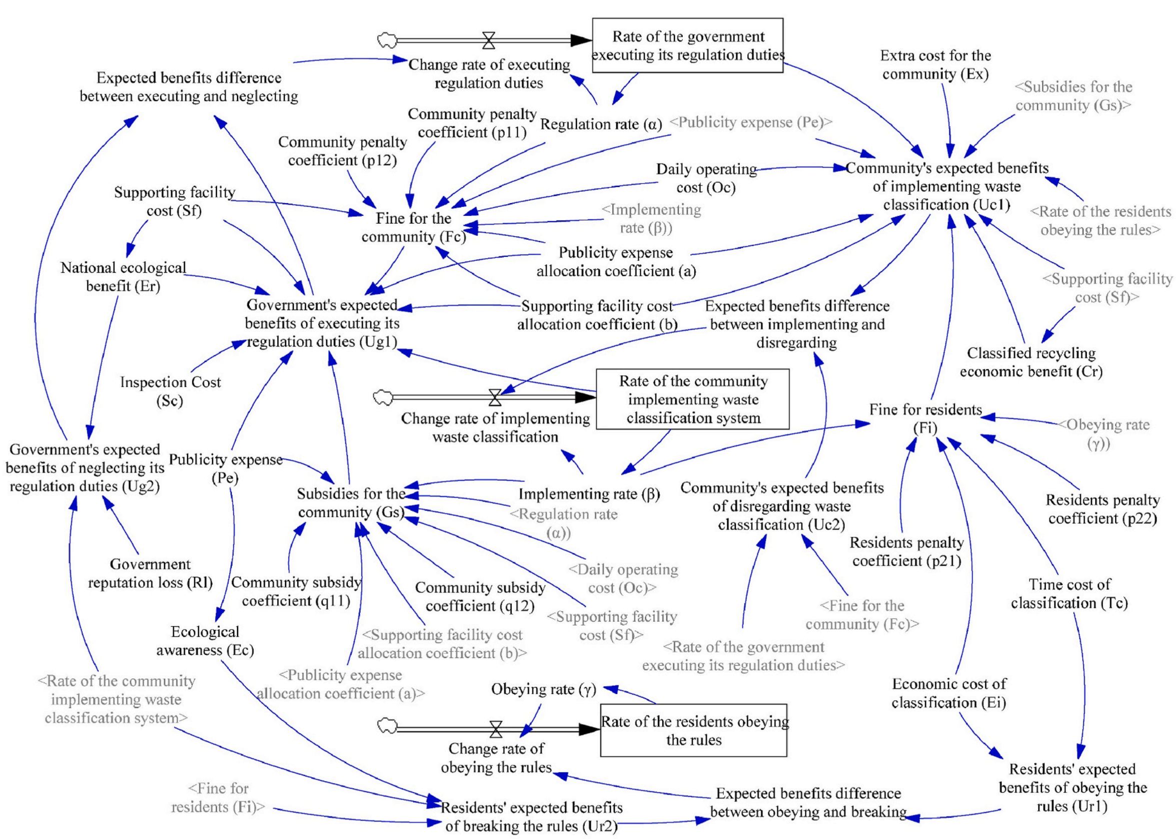

Fig. 12. Modified SD model under the optimal dynamic penalty-subsidy scheme.

is not maximized from a holistic system perspective. Thus, the optimal dynamic penalty-subsidy scheme is proposed (Guo et al., 2018; Wang et al., 2011). In this scheme, the government dynamically imposes penalties and subsidies according to the community's implementation and regulation rates. The community imposes penalties dynamically according to the residents' obedience rate and its implementation rate. The modification can be presented in the following three equations:

$$F_c^{**} = p_{11}F_c(1-\beta) + p_{12}\frac{O_c + (1-b)S_f + (1-a)P_e}{\alpha},$$

$$F_i^{**} = p_{21}F_i(1-\gamma) + p_{22}\frac{T_c + E_i}{\beta}, \tag{18}$$

$$G_s^{**} = q_{11}\beta G_s + q_{12}\frac{\alpha}{O_c + (1-b)S_f + (1-a)P_e}$$

where $p_{11}, p_{12}, p_{21}, p_{22}, q_{11}$, and q_{12} represent corresponding penalty coefficients or subsidy coefficients, which are all set to 1 in this scheme. The modified multi-player evolutionary game SD model is shown in Fig. 12.

Figs. 13 and 14 show the simulation results when the initial strategies of the government, community, and residents are randomly set to $\alpha = 0.5, \beta = 0.5, \gamma = 0.5$ and $\alpha = 0.2, \beta = 0.4, \gamma = 0.8$, respectively.

The simulation results show that, in the optimal dynamic penalty-subsidy scheme, the strategy choices of the government, community, and residents will approach $E^{**}(0, 1, 1)$ asymptotically as the game time increases, which means that this scheme can eliminate the fluctuations in the static penalty scheme and obtain an ideal ESS; that is, the rate of the government executing its regulation duties approaches 0, and the rate of the community implementing waste classification system and the rate of the residents obeying the rules approach 1. Furthermore, given that α appears in the denominator of equation (18), this ESS is $E^{**}(\alpha, 1, 1)$ as a result of $\alpha \neq 0$, in which

$$\lim_{t\to+\infty} \alpha = 0. \tag{19}$$

Similarly, the above simulation results also need to be further verified. For the convenience of analysis, the ESS is analyzed only, namely, $E^{**}(\alpha, 1, 1)$. First, F_c^{**}, F_i^{**} and G_s^{**} are substituted into the replicated dynamic equation set (13), and the Jacobian matrix of this equation set is obtained. When $E^{**}(\alpha, 1, 1)$ is put into the Jacobian matrix, the Jacobian matrix $J(E^{**})$ is shown as follows:

$$J(E^{**}) = \begin{bmatrix} -10.465 + 20.74\alpha + 0.285\alpha^2 \quad (1-\alpha)\left(-13.465\alpha - 10.535 - 0.095\alpha^2\right) \quad 0 \\ 0 - 0.005 - 7.465\alpha - 0.095\alpha^2 \quad 0 \\ 0 \quad 0 \quad -2.88 \end{bmatrix} \tag{20}$$

Given that $\lim_{t\to+\infty} \alpha = 0$, the characteristic values of the Jacobian matrix (20) are as follows:

$$\begin{cases} \lambda_1 = -10.465 + 20.74\alpha + 0.285\alpha^2 < 0 \\ \lambda_2 = -0.005 - 7.465\alpha - 0.095\alpha^2 < 0 \\ \lambda_3 = -2.88 < 0 \end{cases} \tag{21}$$

Therefore, all characteristic values are less than 0, which indicates that $E^{**}(\alpha, 1, 1)$ is the ESS of the evolutionary game. This conclusion is consistent with the simulation results of the SD model.

In conclusion, in a static penalty scheme, the government increases the penalties for the non-compliant community and residents, which can quickly control non-compliance in the short term. However, in the long term, such a scheme increases the fluctuations in non-compliance by the community and residents, making the gaming process more challenging to control. This result is also common in the real world, where the community and residents fail to enforce waste classification strictly in the early stages of implementation, in which case the government will continue to strengthen guidance and introduce tougher laws and regulations. If the community and residents still choose to violate the rules, they will be severely penalized. At this point, the community and residents will be aware of the situation and adjust their strategies dynamically to reduce their violations by observing and comparing the expected benefits. However, over time, the government will gradually relax its guidance on waste classification because enforcing laws and regulations and the construction related to waste classification will objectively increase government costs. The rate of non-compliance by the community and residents then increases, confusing the development of waste classification. The whole process leads to repeated fluctuations and oscillations in implementing waste classification.

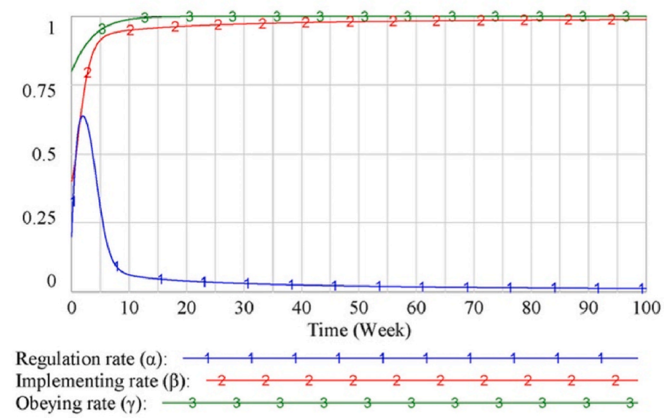

Fig. 14. Game results under the optimal dynamic penalty-subsidy scheme ($\alpha = 0.2, \beta = 0.4, \gamma = 0.8$)

The dynamic penalty scheme can effectively restrain fluctuations in the game process and reduce uncertainty in the development of waste classification, and the steady state is not affected by the initial value of each player's strategy. Furthermore, the optimal dynamic penalty-subsidy scheme can eliminate the fluctuations and an ideal ESS in which the community will nearly choose to implement the waste classification system, and the residents will nearly choose to obey the rules. Therefore, to guide the implementation of waste classification and reduce the incidence of non-compliance by the community and residents effectively, the government should dynamically formulate appropriate penalties and subsidies according to the current situation and main objectives at different times. While avoiding fluctuations in the game, the rate of non-compliance by the community and residents is reduced, promoting the long-term implementation of waste classification. This model provides a good reference for relevant departments to formulate policies. In this way, the community waste classification system can be effectively implemented.

4. Conclusions

The present study examines the problems in implementing China's community waste classification system. We establish a multi-player evolutionary game among the government, community, and residents.

The correctness of the results is verified through SD simulation combined with mathematical analysis. By analyzing the strategy choices of each stakeholder in different schemes, the conclusions drawn from this study are listed along three main topics below.

(1) The use of SD in simulating the multi-player evolutionary game among the government, community, and residents is a practical way to perform stability analysis and identify equilibrium solutions. Furthermore, the SD model is general and universal, which can provide a reference for other developing countries to formulate management strategies for implementing the community waste classification system.
(2) When the penalties are static, the strategy choices of the government, community, and residents fluctuate repeatedly. This game has no ESS, so the behavior of all stakeholders cannot be effectively controlled. In this case, the government has difficulty stably implementing the community waste classification system.
(3) In the dynamic penalty scheme, the game has an ESS, and the fluctuations are effectively eliminated. However, the optimal strategy of the government, community, and residents in this ESS is not good enough. Thus, the optimal dynamic penalty-subsidy scheme is proposed. This scheme can eliminate the fluctuations and allows the dynamical system to converge toward an ideal ESS. This scheme provides a good reference for relevant departments to formulate policies.

However, this study has limitations. This study does not present specific implementation measures for schemes. For example, the government's operation in the optimal dynamic penalty-subsidy scheme is not discussed. The details of the scheme should be investigated in the future to provide more focused advice to facilitate the implementation of waste classification.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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