Co-evolutionary game of manufacturers' abatement behavior under carbon tax-subsidy policy

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Abstract

In the context of carbon tax-subsidy policy, our paper develops the models of the tripartite evolutionary game between consumers, manufacturers and local governments and analyzes the impacts of carbon tax-subsidy policy on the strategies of consumers, manufacturers and local governments. Through the construction of replicated dynamic equations, we get the evolutionary stable strategy. Then, the numerical analysis is performed with system dynamics simulation. The results show that (i) the local governments should strengthen the consumers' awareness of environmental protection through higher financial subsidies, (ii) the taxation intensity coefficient accelerates the dynamic system to evolve into a stable state and (iii) an appropriate punishment by the government accelerates the dynamic system to evolve into a stable state. Our research is expected to provide a reference for local governments to implement effective carbon tax-subsidy policy on manufacturers.

Keywords: evolutionary game; system dynamics; carbon tax- subsidy policy; multi-player game

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Received 12 June 2020; revised 28 September 2020; accepted 30 September 2020

1 INTRODUCTION

With economic development, environmental pollution has been a global crisis. Since the British government first proposed the concept of a 'low-carbon economy' in the energy white paper in 2003, carbon emissions in economic activities have attracted widespread attention worldwide, especially in China [24]. In 2015, China proposed to reach the peak of emissions around 2030 [18].

In 2016, China's 13th Five-Year Plan for Controlling Greenhouse Gas Emissions stipulated that by 2020, carbon intensity will be reduced by 18% compared with 2015 [12].

Environmental issues have become the focus of academic attention. In the past, a few decades ago, global carbon dioxide emissions, which accounted for 65% of the total greenhouse gases, have increased dramatically [10]. Therefore, it is necessary for manufacturers to incorporate environmental protection and sustainable development into the growth of the company. But for excessive investment in clean production and market uncertainty, manufacturers must always balance maximizing their own interests and reducing carbon emissions. Meanwhile, environmental protection issue draw consumers' attention and make them put tremendous pressure on the government and the high price of low-carbon (LC) products has become an obstacle to consumers' choice. In addition, the government is faced with two major problems: pollution control and expansion of LC propaganda. Therefore, it is imperative to adopt corresponding policy actions and effective policy mechanisms to stimulate the clean production market.

Our paper uses evolutionary game theory (EGT) to study the choice of LC strategy. EGT can reflect the relationship between strategy change and payoff fluctuation, to investigate players' interaction behaviors dynamically [14]. Hence, EGT has been widely used in various fields, such as economics [20], supply chain management [25], strategy interaction [13] and players' cooperation [19]. Since EGT has the advantage of dealing with strategy selection, which can be naturally used in the field of LC

International Journal of Low-Carbon Technologies 2021, 16, 1217–1228

https://doi.org/10.1093/ijlct/ctaa081 Advance Access publication 2 June 2021

management. Based on EGT, our research focuses on the strategic interaction of LC policy.

Carbon tax and subsidy are important policy tools for controlling carbon emissions [4, 23, 27], promoting LC technology innovation and optimizing industrial structure [17]. By implementing economic and administrative measures, the government can stimulate manufacturers and consumers to participate in environmental protection, thereby alleviating the carbon emission as soon as possible. In the implementation of this policy, the government should also prevent and control manufacturers' cheat subsidy behavior and take corresponding measures to regulate manufacturers' faking behavior. Therefore, the objectives of our research were to develop the models of the tripartite evolutionary game between consumers, manufacturers and local governments to analyze the impacts of carbon tax-subsidy policy on the decisions of consumers, manufacturers and local governments; and to explore a stable state and main driving factors by using a numerical study.

The reminder of this paper is organized as follows. Section 2 introduces a review of the literature. In Section 3, the problem description is presented and then the tripartite evolutionary game model under carbon tax-subsidy policy is proposed. In Section 4, a numerical example is given to demonstrate the application of the proposed model and to provide management insights. Section 5 summarizes the conclusions and presents the future research.

2 LITERATURE REVIEW

Three streams of literature are highly related to our research: macroscopic analysis of environmental policies, influence of environmental policies on firm decision and application of EGT in environmental policies. In the following section, we review studies relevant to each stream and highlight the differences between this study and the existing literature.

2.1. Macroscopic analysis of environmental policies

Environmental policies contain carbon subsidy/tax regulation and cap-and-trade regulation. From a macro perspective, many scholars have discussed the advantages and disadvantages of environmental policy. Farinelli *et al.* [9] compared energy efficiency under cap-and-trade regulation and carbon subsidy/tax mechanism. Avi-Yonah *et al.* [1] compared carbon subsidy/tax regulation with the implementation of cap-and-trade mechanism and proposed obstacles in the implementation process. A survey conducted in 13 district cities by Duan and Hu [6] for empirical analysis showed that it is necessary to fill the gap between government supervision and local officials' support for executive supervision. Raufer and Li [15] suggested that carbon subsidy/-tax regulation is suitable for developing countries. The above-mentioned studies discuss carbon tax-subsidy regulation from macro perspective. However, they did not study how the local governments' carbon subsidy/tax regulation influences manufacturers and consumers' decision. Under carbon tax-subsidy regulation, we develop a tripartite evolutionary game model to explore synergistic effect among consumers, manufacturers and local governments.

Table 1. *Game parameters.*

	Notations explanation
π_L	The profits of the manufacturer with LC strategy
π_H	The profits of the manufacturer with HC strategy
R_G	Revenue received by the government when environmental policies are not implemented
R_E	The government gains derived from environmental quality improvement
R_1	The utility of consumers from buying LC products
R_2	The utility of consumers from buying HC products
L_1	Governmental intervention cost
L_2	Environment governance cost of the government
T	The taxation for the manufacturer who produces HC products
M	The penalty for manufacturers' faking behavior
s	Subsidies for manufacturer producing LC products
N	Financial subsidies provided by the government to consumers
α	Government subsidy intensity coefficient for LC consumers
γ	Government subsidy intensity coefficient for LC manufacturers
θ	Government taxation intensity coefficient for HC manufacturers
β	Government penalty intensity coefficient for the manufacturer faking behavior

2.2. The influence of environmental policies on firm decision

The game theory is used to study the impact of government environmental policies on firm decision. Du *et al.* [7] used the game model to study the impact of government regulation on emission-dependent supply chain under cap-and-trade regulation. Liu et al. [11] established an evolutionary game model in the context of electric vehicle industry and analyzed the impacts of government carbon tax/subsidy regulation on automobile manufacturers' decision. Wang *et al.* [21] investigated the supply chain enterprise operations strategies and governmental carbon subsidy/tax policy under decentralized and centralized supply chain. Sheu [16] based on bargaining game to investigate the negotiations between firms and reverse logistics suppliers under government regulation. Xu *et al.* [22] compared operational decisions of the firm under carbon subsidy/tax and cap-and-trade mechanisms. Bansal and Gangopadhyay [2] investigated the influence of carbon subsidy/tax mechanism on firms. Bansal [3] studied the impacts of carbon subsidy/tax policy on social welfare. In the above studies, many scholars have employed a general game theory to discuss the influence of government environmental policies in manufacturers decision. Although Liu *et al.* [11] used the EGT as we do, they did not consider the behavior of consumers, which has an important impact on both local governments and manufacturers.

2.3. Application of EGT in environmental policies

EGT has also been applied to environmental policies. Zhang *et al.* [25] used evolutionary game to study the interaction mechanism between manufacturers and governments under cap-and-trade

Table 2. *Strategies and payoffs matrix.*

Strategies			Payoffs matrix		
M	C	G	M	C	G
LC	*BL*	*I*	$\pi_L + \gamma s - \beta M$	$R_1 + \alpha N$	$R_E + \mathrm{R}_G + \beta M - \gamma s - \alpha N - L_1$
LC	*BL*	*NI*	$\pi_L + \gamma s$	$R_1 + \alpha N$	$R_E + \mathrm{R}_G - \gamma s - \alpha N$
LC	*HL*	*I*	$\pi_L + \gamma s - \beta M$	0	$R_E + \mathrm{R}_G + \beta M - \gamma s - L_1$
LC	*HL*	*NI*	$\pi_L + \gamma s$	0	$R_E + \mathrm{R}_G - \gamma s$
HC	*BL*	*I*	$\pi_H - \theta T$	0	$R_G + \theta T - L_1 - L_2$
HC	*BL*	*NI*	π_H	*0*	$R_G - L_2$
HC	*HL*	*I*	$\pi_H - \theta T$	R_2	$R_G + \theta T - L_2 - L_1$
HC	*HL*	*NI*	π_H	R_2	$R_G - L_2$

Notation: {M,C,G} represent {Manufacturers, Consumers, Governments}, respectively.

policy. Chen and Hu [5] applied EGT to investigate manufacturers' strategies under carbon tax and subsidy policy. Zhao and Sun [26] applied EGT to analyze the impact of environmental policy on the innovation and competitiveness of firms empirically. Our study is in the context of carbon tax-subsidy regulation, investigating the multi-party interaction mechanism in the dynamic system composed of manufacturers, consumers and local governments, which is completely different from the above-mentioned papers.

Within these streams, our main contribution lies in the following aspects. First, many scholars have employed a general game theory such as the Nash bargaining game, Stackelberg game to discuss the impacts of government intervention on manufacturers' decisions. This paper develops an evolutionary game model to investigate the impact of government intervention on manufacturers and consumers' decisions. Second, most scholars have ignored the behavior of consumers. The development of the industry is the result of the joint promotion of local governments, manufacturers and consumers. Our study develops a tripartite evolutionary game model to explore synergistic effects among consumers, manufacturers and local governments. Third, we investigate the synergistic effects among consumers, manufacturers and local governments in the context of tax-subsidy policy, our context is unique. This study is designed to provide local governments with some new managerial insights under the background of carbon tax-subsidy regulation.

3 MULTI-PLAYER EVOLUTIONARY GAME

3.1. MODEL DESCRIPTIONS

Following Encarnação *et al.* [8], this multi-player evolutionary game includes local governments, manufacturers and consumers and we assume three players of the game are bounded rationality. The strategy space of manufacturers, including producing of LC products and high-carbon (HC) products, is defined as$M = (LC, HC)$.§ is the probability that manufacturers adopt *LC* strategy and $1 - \S$ represents the probability that manufacturers choose *HC* strategy. The strategy of consumers, incorporating purchasing of LC products (BL) and HC products (BH), is defined as $C = (BL, BH)$. y is the probability that the consumers adopt *BL* strategy and $1 - y$ represents the probability that consumers choose *BH* strategy. The government's strategy space is defined as $G = (I, NI)$. I (intervention) indicates that governments intervene in manufacturers' LC industry and NI (non-intervention) indicates that governments do not supervise the manufacturers' LC industry. z is the probability that governments adopt I strategy and $1-z$ represents the probability that governments adopt *NI* strategy. Hence, the multi-player evolutionary game model is defined as $\ell = \{(\S, 1 - \S), (y, 1 - y), (z, 1 - z)\}$. The associated parameters are listed in Table 1, and individual payoffs are given in Table 2.

3.2. MODEL SETUP

3.2.1. Expected utility of manufacturers

Let U_{11} be the expected utility of the manufacturer whose strategy is LC and U_{12} be the expected utility of the manufacturer whose choice is HC, then the mean utility of manufacturers can be obtained. Let $\overline{U}_1$ represent manufacturers' mean utility; U_{11}, $U_{12}$and $\overline{U}_1$, respectively, are presented as the follows:

$$\begin{aligned} U_{11} &= yx(\pi_L + \gamma s - \beta M) + y(1-z)(\pi_L + \gamma s) \\ &\quad + (1-y)z(\pi_L + \gamma s - \beta M) + (1-y)(1-z)(\pi_L + \gamma s) \\ &= (\pi_L + \gamma s - \beta M) + (\pi_L + \gamma s)(1 - Z) \end{aligned} \tag{1}$$

$$U_{12} = \pi_H \theta T + \pi_H (1 - z) \tag{2}$$

$$\overline{U}_1 = xU_{11} + (1 - x)U_{12} \tag{3}$$

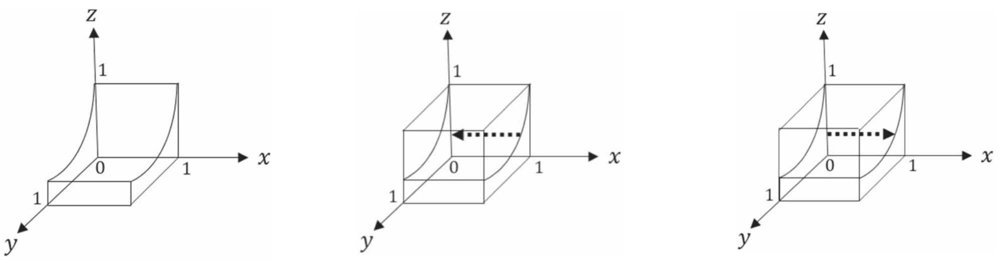
3.2.2. Expected utility of consumers

Let U_{21} be the expected utility of the consumer whose strategy is BL and U_{22} be the expected utility of the consumer whose choice is BH, then the mean utility of consumers is obtained. Let $\overline{U}_2$ represent consumers' mean utility and U_{21}, $U_{22}$and $\overline{U}_2$ are presented as the follows:

$$U_{21} = (R_1 + \alpha N)x \tag{4}$$

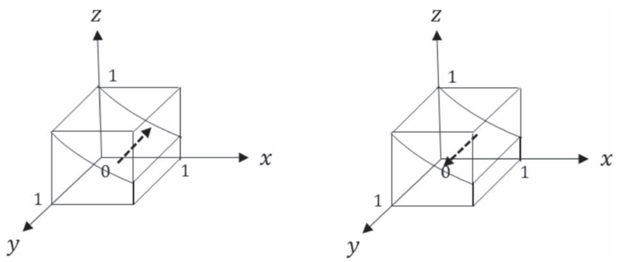
$$\overline{U}_{22} = xR_2 \tag{5}$$

$$\overline{U}_1 = xU_{11} + (1 - x)U_{12} \tag{6}$$



(i) $z^* = 2 - A$ (ii) $z > 2 - A$ (iii) $z < 2 - A$ or $A < 1$

Figure 1. *Evolutionary dynamics of manufacturers under different conditions.*



(i) $R_1 + \alpha N - R_2 < 0$ (ii) $R_1 + \alpha N - R_2 > 0$

Figure 2. *Evolutionary dynamics of consumers under different conditions.*

3.2.3. Expected utility of governments

Let U_{31} be the expected utility of government whose strategy is I and U_{32} be the expected utility of government whose choice is NI, then the mean utility of governments is obtained. Let $\overline{U}_3$ represent governments' mean utility and U_{31}, $U_{32}$and $\overline{U}_3$, respectively, are presented as the follows:

$$U_{31} = (R_{31} + R_G + \beta M - \gamma s - \alpha N - L_1)xy + x(1-y) \quad (7)$$

$$(R_E + RG + \beta M - \gamma s - L_1) + (1-x)y$$

$$(R_G + \theta T - L_1 - L_2)$$

$$U_{32} = xy(R_E + R_G - \gamma s - \alpha N) + (R_E + R_G - \gamma s)x \quad (8)$$

$$(1-y) + (1-x)y(R_G - L_2) + (1-x)(1-y)(R_G - L_2)$$

$$\overline{U}_3 = zU_{31} + (1-z)U_{32} \quad (9)$$

3.3. REPLICATOR DYNAMIC EQUATIONS

The replicator dynamic equations of strategy LC adopted by manufacturers $F(x)$ is obtained as

$$F(x) = \frac{\partial x}{\partial t} = x(U_{11} - \overline{U}_1) = x(1-x)((2-z)(\pi_L - \pi_H + \gamma s) - \beta M + \theta T) \quad (10)$$

The replicator dynamic equations of strategy BL adopted by consumers $F(y)$ and strategy I selected by governments $F(z)$ are obtained as

$$F(y) = \frac{\partial y}{\partial t} = y(U_2 1 - \overline{U}_2) = xy(1-y)(R_1 + \alpha N - R_2) \quad (11)$$

$$F(y) = \frac{\partial z}{\partial t} = z(U_3 1 - \overline{U}_3) = z(1-z)((\beta M - \theta T - L_1) \quad (12)$$

3.4. THE STABILITY ANALYSIS OF THE MODEL

According to the multi-player dynamic system, the equilibrium point of this evolutionary game is inferred Figures 1–3.

Let $F(\S) = \frac{\partial x}{\partial t} = 0$, we can obtain three equilibrium points, $x^* = 0$, $x^* = 1$ and $z^* = 2 - \frac{\beta M - \theta T}{\pi_L - \pi_H + \gamma s}$. ESS should satisfy $\frac{\partial F(\S)}{\partial x} < 0$ and $F(\S) = 0$ simultaneously, the following situations are discussed.

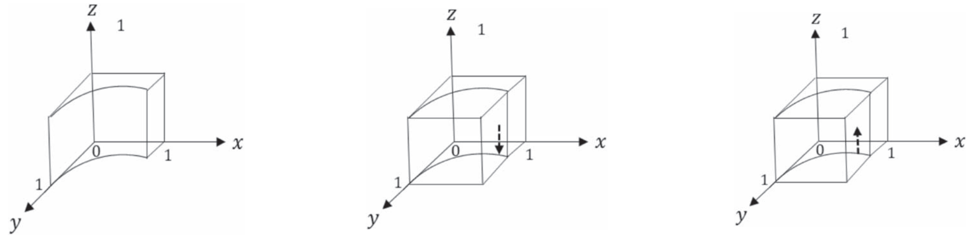
(1) If $z^* = 2 - \frac{\beta M - \theta T}{\pi_L - \pi_H + \gamma s}$, $F(\S)$ is always equal to zero. This suggests that the manufacturers' choice of strategy does not change over time.

(2) If $\frac{\beta M - \theta T}{\pi_L - \pi_H + \gamma s} < 1$, by taking the first-order partial derivation of $F(\S)$ with respect to $\S$, we can obtain$\frac{\partial F(\S)}{\partial x} = (1 - 2\S)((2-z)(\pi_L - \pi_H + \gamma s) - \beta M + \theta T)$. $x^* = 1$ is the equilibrium point.

(3) If $z < 2 - \frac{\beta M - \theta T}{\pi_L - \pi_H + \gamma s}$,$x^* = 1$ is the ESS. If $z > 2 - \frac{\beta M - \theta T}{\pi_L - \pi_H + \gamma s}$, then $x^* = 0$ is the equilibrium point.

Let $F(y) = \frac{\partial y}{\partial t} = 0$, we can obtain three equilibrium points, $y^* = 0$, $x^* = 1$ and $y^* = 1$. The equilibrium point should satisfy $\frac{\partial F(y)}{\partial y} < 0$ and $F(y) = 0$ simultaneously, the following situations are discussed.

(1) If $x^* = 0$, $F(y)$ is always equal to zero. This suggests that the consumers' choice of strategy does not change over time.



(i) $x^* = \frac{L_1 - \theta T}{\beta M - \theta T}$ (ii) $x < \frac{L_1 - \theta T}{\beta M - \theta T}$ (iii) $x > \frac{L_1 - \theta T}{\beta M - \theta T}$

Figure 3. *Evolutionary dynamics of goverments under different conditions.*

Table 3. *Asymptotic stability analysis of co-evolutionary game.*

Strategy	Symbol of eigenvalue	State
(0,0,0)	There are positive eigenvalues.	Instability point
(0,1,0)	There are positive eigenvalues.	Instability point
(0,1,1)	There are positive eigenvalues.	Instability point
(0,0,1)	There are positive eigenvalues.	Instability point
(1,1,0)	There are positive eigenvalues.	Instability point
(1,0,1)	There are positive eigenvalues.	Instability point
(1,0,0)	There are positive eigenvalues.	Instability point
(1,1,1)	If $(\pi_L - \pi_H + \gamma s) - \beta M + \theta T > 0, R_1 + \alpha N - R_2 > 0$ and $\beta M - L_1 > 0$, then symbol of eigenvalue is negative.	ESS

(2) If $R_1 + \alpha N - R_2 < 0$, by taking the first-order partial derivation of $F(y)$ with respect to y, we can obtain $\frac{\partial F(y)}{\partial y} = x(1 - 2y)(R_1 + \alpha N - R_2)$; thus, $y^* = 0$ is the equilibrium point.

(3) If $R_1 + \alpha N - R_2 > 0$, then$y^* = 1$ is the equilibrium point.

Let $F(z) = \frac{\partial z}{\partial t} = 0$, we can obtain three equilibrium points, $y^* = 0$, $x^* = 1$ and $y^* = 1$. Equilibrium point should satisfy $\frac{\partial F(z)}{\partial z} < 0$ and $F(z) = 0$ simultaneously, the following situations are discussed.

(1) If $x^* = \frac{L_1 - \theta T}{\beta M - \theta T}$, $F(z)$ always equals to zero. This suggests that the governments' choice of strategy does not change over time.

(2) If $x < \frac{L_1 - \theta T}{\beta M - \theta T}$, by taking the first-order partial derivation of $F(z)$ with respect to z, we can obtain $\frac{\partial F(z)}{\partial z} = (1 - 2z)((\beta M - \theta T)\S + \theta T - L_1)$; thus, $z^* = 0$ is the equilibrium point.

(3) If $x > \frac{L_1 - \theta T}{\beta M - \theta T}$, then$z^* = 1$ is the equilibrium point.

3.5. THE ASYMPTOTIC STABILITY ANALYSIS OF THE MODEL

Based on the above analysis, there are eight local equilibrium points in the dynamic system: (0,0,0), (0,0,1), (0,1,0), (0,1,1), (1,0,0), (1,1,0), (1,0,1) and (1,1,1). and the asymptotic stability analysis are given in Table 3. Then, we analyze the local stability of the equilibrium point according to the Jacobian matrix J.

$$J = \begin{bmatrix} \partial F(x)/\partial x & \partial F(x)/\partial y & \partial F(x)/\partial z \\ \partial F(y)/\partial x & \partial F(y)/\partial y & \partial F(y)/\partial z \\ \partial F(z)/\partial x & \partial F(z)/\partial y & \partial F(z)/\partial z \end{bmatrix}$$

$$= \begin{bmatrix} (1 - 2\S)\left((2 - z)(\pi_L - \pi_H + \gamma s) - \beta M + \theta T\right) & 0 & \S(1 - \S)(\pi_H - \pi_L - \gamma s) \\ y\left(1 - y\right)(R_1 + \alpha N - R_2) & x\left(1 - 2y\right)(R_1 + \alpha N - R_2) & 0 \\ z(1 - z)(\beta M - \theta T) & 0 & (1 - 2z)\left((\beta M - \theta T)\S + \theta T - L_1\right) \end{bmatrix}$$

We take (1,1,1) as the example and discuss whether (1,1,1) is asymptotic stable or not. The Jacobian matrix of the system at (1,1,1) is

$$J_{(1,1,1)} = \begin{bmatrix} -\left((\pi_L - \pi_H + \gamma s) - \beta M + \theta T\right) & 0 & 0 \\ 0 & -(R_1 + \alpha N - R_2) & 0 \\ 0 & 0 & -\left((\beta M - \theta T) + \theta T - L_1\right) \end{bmatrix}$$

The characteristic equation of $J_{(1,1,1)}$ is$J_{(1,1,1)}{}' = \lambda E - J_{(1,1,1)}$, let $|J_{(1,1,1)}{}'| = 0$, the characteristic roots can be obtained as $\lambda_1 = -((\pi_L - \pi_H + \gamma s) - \beta M + \theta T)$, $\lambda_2 = -(R_1 + \alpha N - R_2)$, $\lambda_3 = -((\beta M - \theta T) + \theta T - L_1)$, (1,1,1) is asymptotic stable that needs to meet the condition $(\pi_L - \pi_H + \gamma s) - \beta M + \theta T > 0, R_1 + \alpha N - R_2 > 0$ and $(\beta M - \theta T) + \theta T - L_1 > 0$ simultaneously.

Usually, let equations (10)–(12) equal to zero, we can obtain two mixed strategies of manufacturers, consumers and local governments.

$$\begin{cases} (x_1^*, y_1^*, z_1^*) = \left(\frac{L_1 - \theta T}{\beta M - \theta T}, 0, \frac{2\pi_H + 2\pi_L - \beta M + 2\gamma s + \theta T}{\pi_H + \pi_L + \gamma s}\right) \\ (x_2^*, y_2^*, z_2^*) = \left(\frac{L_1 - \theta T}{\beta M - \theta T}, 1, \frac{2\pi_H + 2\pi_L - \beta M + 2\gamma s + \theta T}{\pi_H + \pi_L + \gamma s}\right) \end{cases} . \quad (13)$$

We discuss whether (x_i^*, y_i^*, z_i^*) is asymptotically stable or not. The Jacobian matrix of the system at (x_i^*, y_i^*, z_i^*) is

$$J_{(x_i^*,y_i^*,z_i^*)} = \begin{bmatrix} 0 & 0 & 0 \\ 0 & \frac{L_1-\theta T}{\beta M-\theta T}(R_1+\alpha N-R_2) & 0 \\ -\frac{(\pi_H+\pi_L-\beta M+\gamma s+\theta T)(2\pi_H+2\pi_L-\beta M+2\gamma s+\theta T)}{(\pi_H+\pi_L+\gamma s)^2}(\beta M-\theta T) & 0 & 0 \end{bmatrix},$$

i = 1,2.

The characteristic equation of $J_{(x_i^*,y_i^*,z_i^*)}$ is$J_{(x_i^*,y_i^*,z_i^*)}{}' = \lambda E - J_{(x_i^*,y_i^*,z_i^*)}$, let $|J_{(x_i^*,y_i^*,z_i^*)}{}'| = 0$, the characteristic roots can be obtained as $\lambda_1 = \lambda_2 = 0$, $\lambda_3 = \frac{L_1-\theta T}{\beta M-\theta T}(R_1 + \alpha N - R_2)$, then (x_i^*, y_i^*, z_i^*) is not asymptotically stable.

From what has been discussed above, there only exists one asymptotically stable point (1,1,1), which need to meet the condition $(\pi_L - \pi_H + \gamma s) - \beta M + \theta T > 0$, $R_1 + \alpha N - R_2 > 0$ and $\beta M - L_1 > 0$ simultaneously. The final stable state of evolution depends on the initial conditions.

4 NUMERICAL STUDY

We simulate the evolutionary behaviors of manufacturers, local governments and consumers under various input strength coefficient, respectively, which could theoretically be applied in many other LC manufacturing industries. The software MATLAB R2018a is used for the co-evolutionary game model simulation. Four scenarios were built to investigate how the tripartite evolution of dynamic system. Scenario 1 investigated the influence of α on evolution of dynamic system. Scenario 2 examined the influence of γ on evolution of dynamic system. Scenario 3 analyzed the effect of θ on evolution of dynamic system. Scenario 4 studied the impact of β on evolution of dynamic system.

The annual output data of enterprises are mainly derived from Chinese official statistics such as the national statistical database and industry association statistics. According to the data, we choose 92 manufacturers in China and 15 of them have produced energy saving. Thus, the initial value of x is 0.15. Consumer choice is influenced by local government policies, the initial value of y is 0.5, we choose 0.5 as the initial value of z. The main purpose of this study is to analyze the interaction among local governments, manufacturers and consumers. The initial parameters are shown as Table 4.

4.1. The influence of α on the tripartite evolution of dynamic system

$\alpha = 0.2, 0.5, 0.9$ represents low, medium and high government subsidy intensity coefficient for LC consumers, respectively. The corresponding evolution results are shown in Figures 4–7.

Under a different government subsidy intensity coefficient for LC consumers, when local governments subsidize consumers' LC behaviors appropriately, manufacturers evolve to produce clean products and consumers choose to buy LC products to maintain stability. When the subsidy is relatively low, manufacturers evolve to produce clean products and consumers do not choose to buy LC products; the government regulation cannot get the desired effect. Moreover, the larger α is, the faster dynamic system evolves into the point (1,1,1).

The evolutionary trajectory of manufacturers under various government subsidy intensity coefficients for consumers over time is shown in Figure 5. Figure 5 demonstrates governmental subsidies to consumers do not affect the manufacturers evolve into LC production direction. Local government subsidy to consumers directly affects the utility of consumers and it has a huge impact on consumers' strategic choice. Figure 6 shows the evolutionary trajectory of consumers under various government subsidy intensity coefficients. When local governments subsidize consumers at a low intensity, the consumers' strategic choice will evolve into buy HC products. When local government subsidizes consumers with moderate intensity, some consumers will choose the wait-and-see strategy temporarily and give up buying LC products. But with the passage of time, the market environment for manufacturers under government supervision has been gradually improved. More and more manufacturers produce LC products with qualified technology and high safety coefficient, more consumers choose to buy LC products. The ultimate consumers' strategy evolved into buy LC products. When the intensity of subsidies provided by the government to consumers is high, consumers are the most direct beneficiaries and consumers' strategic choice evolves toward the direction of purchasing LC products. Moreover, the more local governments subsidize consumers, the faster evolution speed of consumers purchasing LC products will be. Figure 7 reveals the evolutionary trajectory of local governments under various government subsidy intensity coefficients. Figure 7 shows that government subsidies to consumers do not affect the local governmental evolution into the direction of intervention; the strategy of local governments will gradually evolve into intervention strategy over time.

4.2. The influence of γ on the tripartite evolution of dynamic system

$\gamma = 0.1, 0.5, 0.9$ represents low, medium and high government subsidy intensity coefficient for manufacturers, respectively. The corresponding evolution results are shown in Figures 8–11.

Under a different government subsidy intensity coefficient for manufacturers, when local governments subsidize manufacturers' LC behaviors appropriately, manufacturers evolve to produce clean products, consumers choose to buy LC products and local governments take intervention strategy to maintain stability. When the subsidy is relatively low, manufacturers evolve into produce clean products, consumers choose to buy LC products and local governments take non-intervention strategy to maintain

Table 4. *Initial value of the parameters.*

Parameter	x	y	z	π_L	π_H	R_1	R_2	L_1	L_2	T	M	s	N
Value	0.15	0.5	0.5	1.3	1.1	0.17	0.2	0.002	0.001	0.003	0.005	0.002	0.1

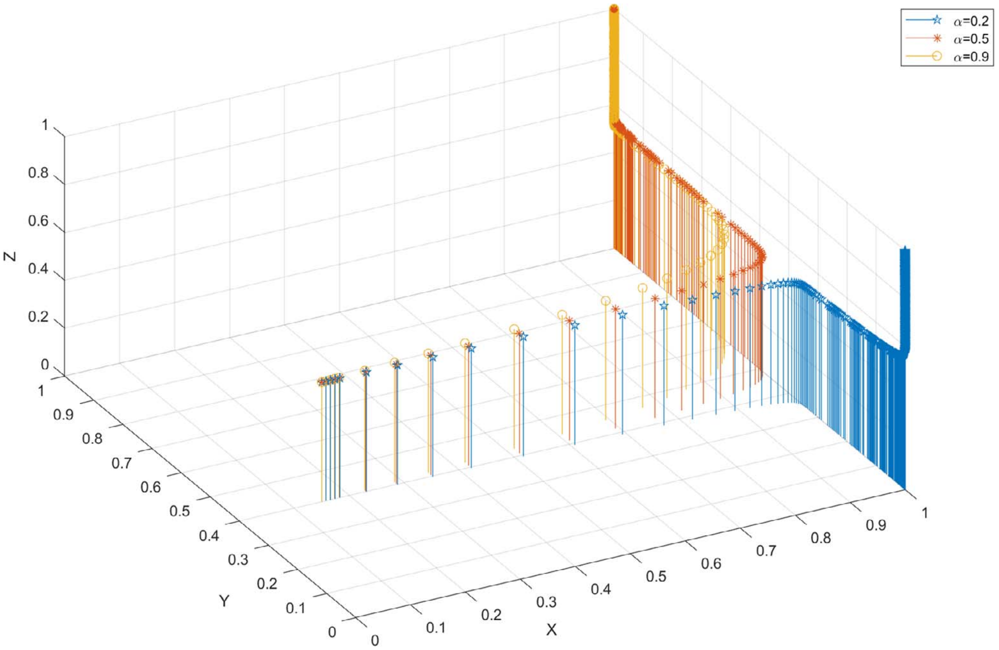


Figure 4. *Tripartite evolution of dynamic system under various government subsidy intensity coefficients for consumers.*

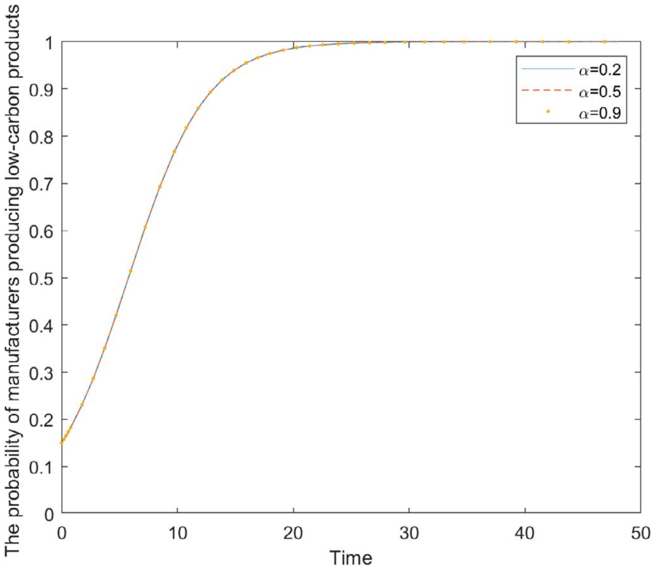


Figure 5. *The evolutionary trajectory of manufacturers under various government subsidy intensity coefficients for consumers.*

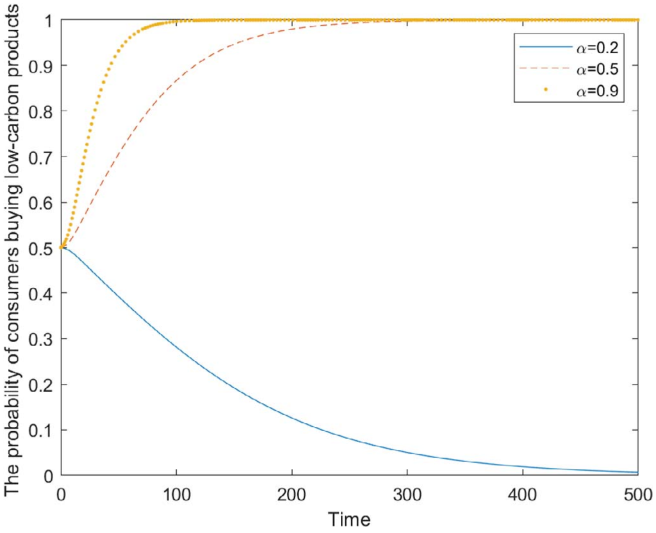


Figure 6. *The evolutionary trajectory of consumers under various government subsidy intensity coefficients for consumers.*

stability, the government regulation cannot get the desired effect. Moreover, the larger government subsidy intensity coefficient for manufacturers is, the faster the dynamic system evolves into the point (1,1,1).

The evolutionary trajectory of manufacturers under various government subsidy intensity coefficients for manufacturers over time is shown in Figure 9. Figure 9 demonstrates government subsidies to manufacturers affect the manufacturers' evolution

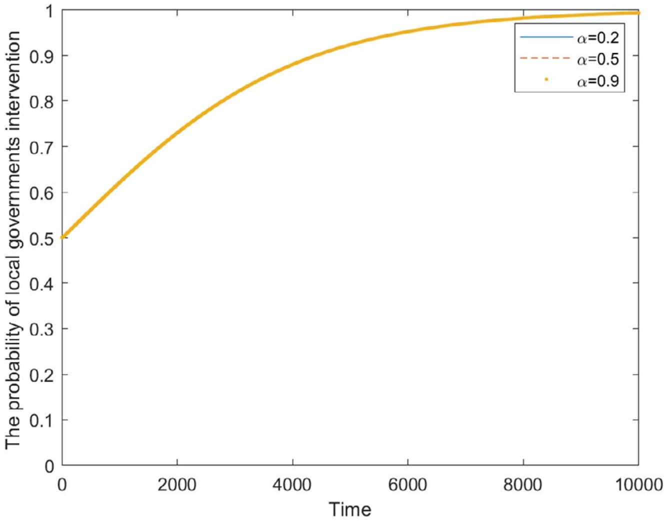


Figure 7. *The evolutionary trajectory of local governments under various government subsidy intensity coefficients for consumers.*

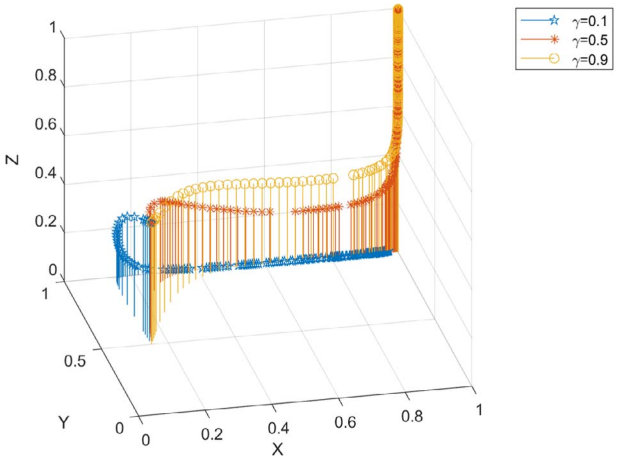


Figure 8. *Tripartite evolution of dynamic system under various government subsidy intensity coefficients for manufacturers.*

into LC production direction. Local government's subsidy to manufacturers directly affect the utility of manufacturers, when local governments subsidize manufacturers at a low intensity, manufacturers have chosen a LC production strategy to evolve very slowly. This is because China's clean production technology started late, the technology is immature, the research and development costs for the core technology are high and the manufacturers are difficult to pay high R&D expenses, so the evolution rate of manufacturers to choose LC production strategies is very slow. When local governments subsidize manufacturers at a high intensity, it can reduce the research and development cost of LC technology in manufacturers, stimulate the enthusiasm of technological innovation and further promote the evolution of manufacturers to clean production. Therefore, the larger government subsidy intensity coefficient for manufacturers is, the faster the manufacturers will evolve into produce LC products.

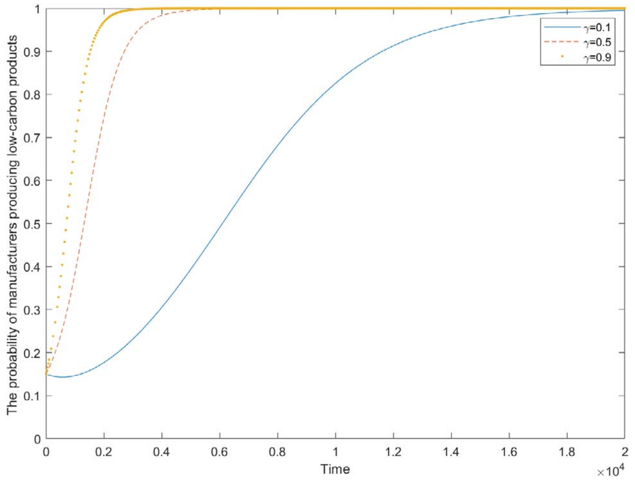


Figure 9. *The evolutionary trajectory of manufacturers under various government subsidy intensity coefficients for manufacturers.*

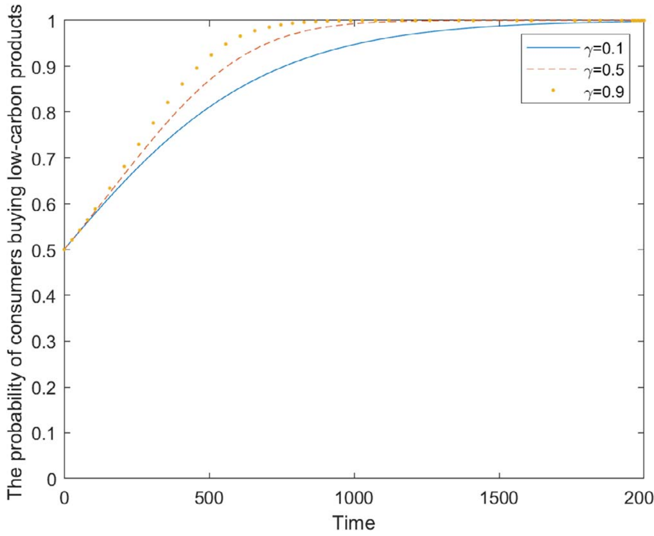


Figure 10. *The evolutionary trajectory of consumers under various government subsidy intensity coefficients for manufacturers.*

Figure 10 shows the evolutionary trajectory of consumers under various government subsidy intensity coefficients for manufacturers. When local governments subsidize manufacturers at a low intensity, consumers have chosen a buying LC products strategy to evolve very slowly. When the intensity of subsidies to manufacturers is high, consumers have chosen a buying LC products strategy to evolve very quickly. The subsidies granted by local governments to the technology research and development of manufacturers have affected the production behavior of enterprises, which has led to changes in consumer purchasing behavior. Therefore, low subsidy is not conducive to consumers purchasing LC products and high subsidies promote consumers to choose LC products.

Figure 11 reveals the evolutionary trajectory of local governments under various government subsidy intensity coefficients

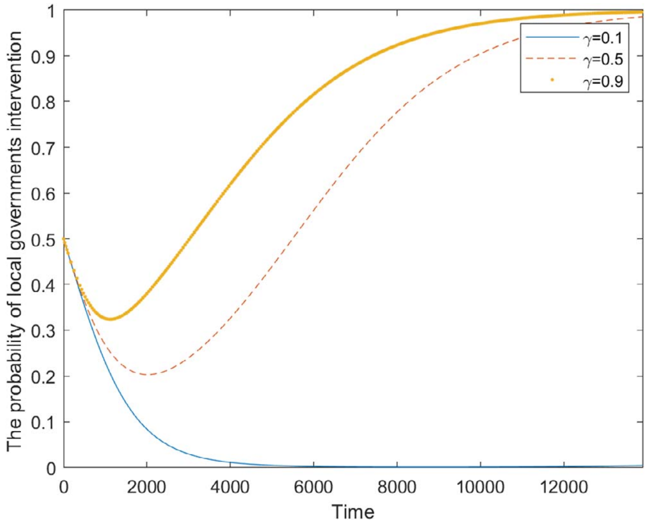


Figure 11. *The evolutionary trajectory of local governments under various government subsidy intensity coefficients for manufacturers.*

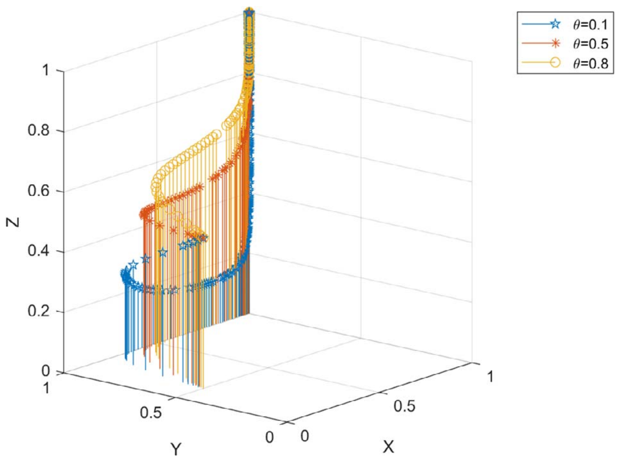


Figure 12. *Tripartite evolution of manufacturers under various government taxation intensity coefficients.*

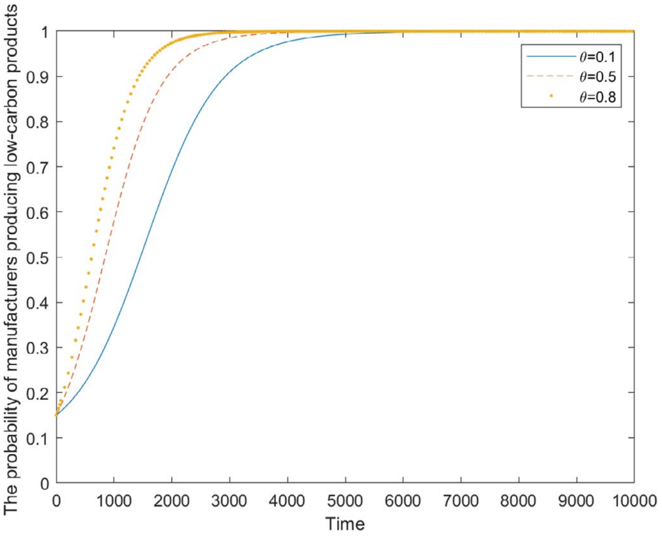


Figure 13. *The evolutionary trajectory of manufacturers under various government taxation intensity coefficients.*

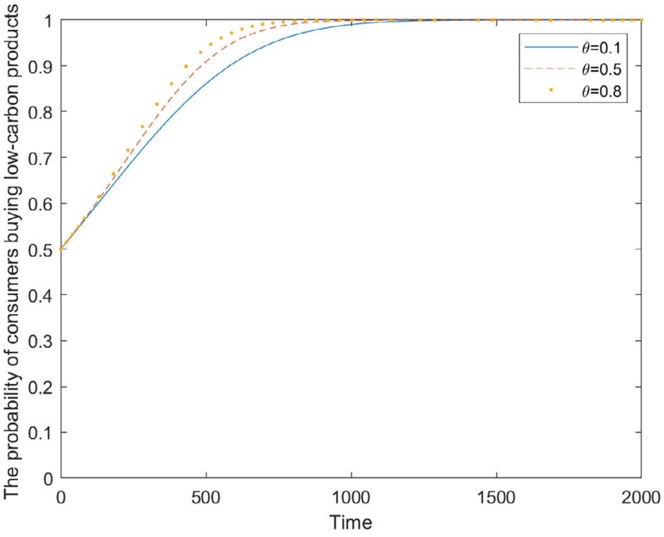


Figure 14. *The evolutionary trajectory of consumers under various government taxation intensity coefficients.*

for manufacturers. Figure 11 shows government subsidies to manufacturers do affect the local government's evolution direction. When local governments subsidize manufacturers at a low intensity, local governments evolve to non-intervention strategy. When local governments subsidize manufacturers with moderate intensity, local governments have chosen intervention strategy to evolve. While subsidizing the technology research and development of manufacturers, local governments must strengthen the supervision of corporate behavior and regulate the market order, in order to continuously improve the LC research and development performance of manufacturers and the efficiency of local government fiscal expenditure.

4.3. The influence of θ on the tripartite evolution of dynamic system

$\theta = 0.1$, 0.5, 0.8 represents low, medium and high government taxation intensity coefficient for HC manufacturers, respectively. The corresponding evolution results are shown in Figures 12–15.

Under a different government taxation intensity coefficient, no matter manufacturers are taxed at any rate, manufacturers evolve to produce clean products, consumers choose to buy LC products and local governments take intervention strategy to maintain stability. In addition, the greater the taxation intensity coefficient, the greater the speed at which the dynamic system evolves to the point (1,1,1).

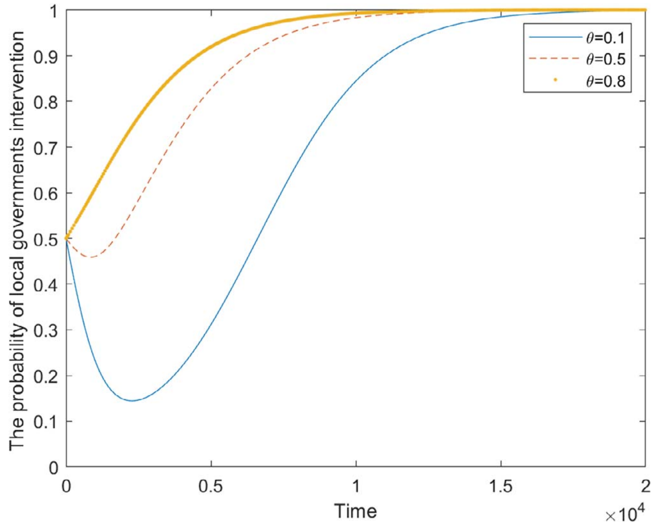


Figure 15. *The evolutionary trajectory of local governments under various government taxation intensity coefficients.*

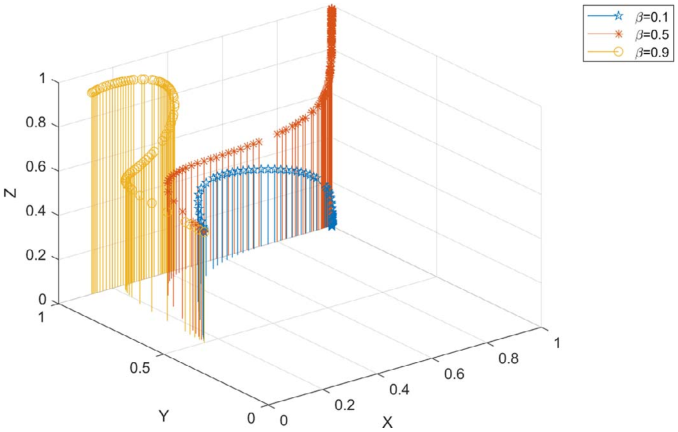


Figure 16. *Tripartite evolution of manufacturers under various government penalty intensity coefficients for the manufacturer faking behavior.*

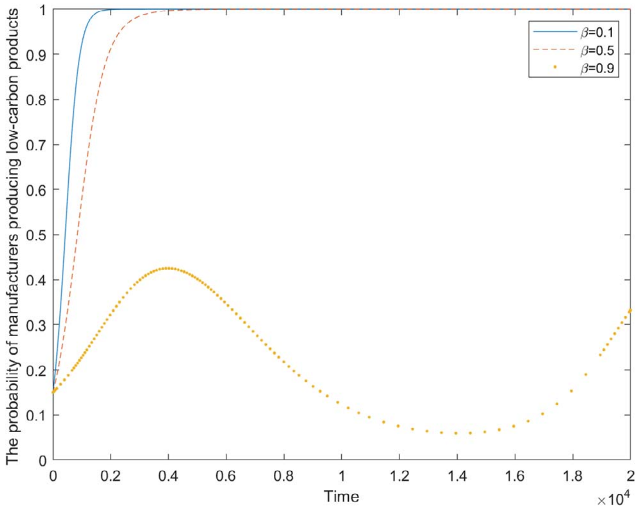


Figure 17. *The evolutionary trajectory of manufacturers under various government penalty intensity coefficients for the manufacturer faking behavior.*

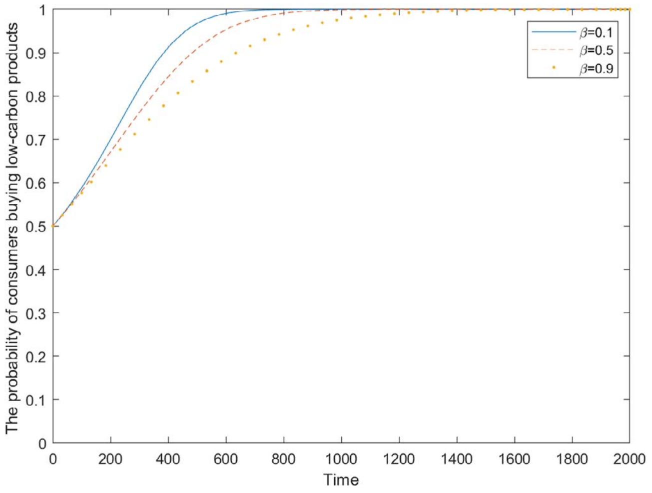


Figure 18. *The evolutionary trajectory of consumers under various government penalty intensity coefficients for the manufacturer faking behavior.*

The evolution trajectory of manufacturers under various government taxation intensity coefficients over time is shown in Figure 13. Figure 13 demonstrates government taxation intensity coefficient affect the manufacturers' evolution into LC production direction. When local governments taxed on manufacturers at a low intensity, manufacturers have chosen a LC production strategy to evolve very slowly. When local governments taxed on manufacturers at a high intensity, manufacturers have chosen a LC production strategy to evolve more quickly. Imposing higher taxes on HC manufacturers forces these enterprises to move toward LC producing strategy in a faster way.

Figure 14 shows the evolutionary trajectory of consumers under various government taxation intensity coefficients. When local governments taxed on manufacturers at a low intensity, consumers have chosen a buying LC products strategy to evolve very slowly. When local governments taxed on manufacturers at a high intensity, consumers have chosen a buying LC products strategy to evolve very quickly. The taxation granted by local governments to the HC products of manufacturers has affected the production behavior of enterprises, which has led to changes in consumer purchasing behavior. Therefore, low taxation is not conducive to consumers purchasing LC products and high taxation promotes consumers to choose LC products.

Figure 15 reveals the evolutionary trajectory of local governments under various government taxation intensity coefficients. Figure 15 shows government taxation intensity coefficient does not affect the local governments' evolution into intervention direction; the strategy of local governments will gradually evolve into intervention strategy over time. In addition, the rate of evolution increases as government taxation intensity coefficient increases.

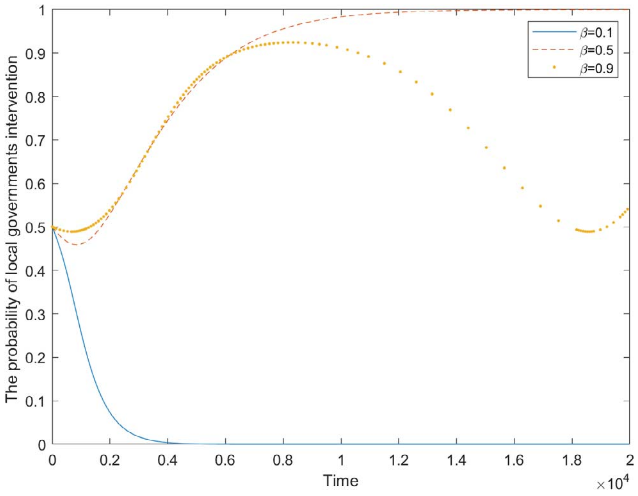


Figure 19. *The evolutionary trajectory of local governments under various government penalty intensity coefficients for the manufacturer faking behavior.*

4.4. The influence of β on the tripartite evolution of dynamic system

$\beta = 0.1, 0.5, 0.9$ represents low, medium and high government penalty intensity coefficient for the manufacturer faking behavior, respectively. The corresponding evolution results are shown in Figures 16–19.

Under a different government penalty intensity coefficient for the manufacturer faking behavior, when local governments punish manufacturer's faking behavior appropriately, manufacturers evolve to produce clean products; consumers choose to buy LC products and local governments take intervention strategy to maintain stability. When government penalty intensity coefficient is relatively low, manufacturers evolve to produce clean products, consumers choose to buy LC products and local governments take non-intervention strategy to maintain stability; the government regulation cannot get the desired effect. When government penalty intensity coefficient is relatively high, the dynamic system will no longer be stable. (Figure 16).

The evolutionary trajectory of manufacturers under various government penalty intensity coefficients for the manufacturer faking behavior is shown in Figure 17. When the government penalty intensity coefficient is high, with the increase of game frequency, the fluctuation amplitude of the probability of manufacturers choosing LC strategy increases gradually, this makes the market unstable. When the government penalty intensity coefficient is moderate, manufacturers have chosen an LC production strategy to evolve. Imposing lower penalty on manufacturers' faking behavior forces these enterprises to move toward LC-producing strategy in a faster way. Figure 18 demonstrates the government will punish manufacturers for cheating subsidies; local governments' intervention behavior will promote manufacturers to produce LC products and continuously improve their clean production technology. Then, this behavior can bring more value to consumers, and promote the development of green production of manufacturers. Figure 19 reveals the evolutionary trajectory of local governments under various government penalty intensity coefficients for the manufacturer faking behavior. When the government penalty intensity coefficient is high, with the increase of game frequency, the fluctuation amplitude of the probability of local governments adopting intervention strategy increases gradually, this makes the market unstable. When government penalty intensity coefficient is moderate, the strategy of local governments will gradually evolve into intervention strategy over time. When government penalty intensity coefficient is relatively low, the strategy of local governments will gradually evolve into non-intervention strategy over time.

5 CONCLUSIONS

The tripartite evolutionary game model is beneficial to the dynamic analysis of players' stability strategies in supply chain management. Moreover, the relevant coefficient was changed to simulate the evolutionary path of the participants' behavior and determine the main driving forces. Based on the case study, the following conclusions are proposed.

(1) Local governments should strengthen consumers' awareness of environmental protection through higher financial subsidies. Consumer environmental behavior accelerated dynamic system evolves into a stable state quickly. Thus, local governments should stimulate consumers to buy green products. Multiple media, such as the internet and broadcasting, should be adopted in advocating the importance of LC products.

(2) Local governments subsidize manufacturers for LC production. The greater the funding, the more favorable it is for the manufacturers to overcome green technical barriers. Local governments must strengthen the supervision of corporate behavior and regulate the market order, in order to continuously improve the LC research and development performance of enterprises and the efficiency of local government fiscal expenditure.

(3) The taxation intensity coefficient accelerated the dynamic system evolves into a stable state. Carbon emission taxation can be used to improve enterprises' social responsibility. Thus, taxation can effectively regulate the behavior of manufacturers and reduce carbon emission.

(4) Appropriate punishment by the government accelerated the dynamic system evolves to a stable state. If the punishment is too severe, the dynamic system will be unstable. If the punishment is insufficient, the government will relax regulation, which is not conducive to the healthy development of the market.

There are several future research directions for this paper. The consumers' LC preference influences the dynamic system; we can consider the impact of consumers' LC preference on the co-evolutionary game. The current work assumes that the information among multi-players is symmetry. In reality, information among multi-players is asymmetry. It is interesting to explore the co-evolutionary game under information asymmetry. Furthermore, the government implements more than one environmental policy; we can study the co-evolutionary game under cap-and-trade regulation.

ACKNOWLEDGMENTS

The authors are grateful to the anonymous editors and the referees for their suggestions and comments.

FUNDING

This research was supported by the National Natural Science Foundation of China (71373157), Innovation Program of Shanghai Municipal Education Commission (2017-01-07-00-10-E00016), Outstanding Innovative Talents for Graduate Students of Shanghai Maritime University (2019YBR012) and Humboldt Research Award Germany (to P.M.P.).

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