Rev. Int. Contam. Ambie. 38 (Sustainable Architecture and Urban Environment) 199-215, 2022
https://doi.org/10.20937/RICA.54463

RESEARCH ON EVOLUTIONARY GAME OF THE TRANSFORMATION OF GREEN TECHNOLOGICAL INNOVATION IN MANUFACTURING INDUSTRIES UNDER ENVIRONMENTAL REGULATION

Investigación sobre el juego evolutivo de la transformación de la innovación tecnológica verde en las industrias manufactureras bajo regulación ambiental

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(Reeived: June 2021; accepted October 2021)

Key words: command-and-control, market-based incentive, public participation, dual logic

ABSTRACT

As the product of the combination of the concept of sustainable development and the transformation of traditional manufacturing industries, green technological innovation will be affected by various factors, such as the willingness of subject of innovation, environmental regulation and so on. How to research the evolution law of the transformation of green technological innovation in manufacturing industries from the perspective of concept-behavior dual logic coupling is the focus of academia. This composition breaks through the traditional limitation of only studying green technological innovation from the perspective of behavior logic, and brings the conceptual logic of the subject into the perspective of research. It designs the mechanism of the transformation of green technological innovation in manufacturing industries driven by internal and external factors, constructs a three-party evolutionary game model of manufacturing-government-consumer, and mobilizes Matlab software to simulate. Thus, the effects of environmental regulations with different intensities on the transformation of green technology innovation in manufacturing industries are revealed, to provide a theoretical basis for environmental regulations to guide it.

Palabras clave: commando y control, incentivo a regulación ambiental con base en el mercado, participación pública, lógica dual

RESUMEN

Como producto de la combinación del concepto de desarrollo sostenible y la transformación de las industrias manufactureras tradicionales, la innovación tecnológica ecológica se verá afectada por diversos factores, como la voluntad de los sujetos de innovación, la regulación ambiental y así sucesivamente. Cómo investigar la ley de evolución de la transformación de la innovación tecnológica verde en las industrias manufactureras desde la perspectiva del acoplamiento de la lógica dual de concepto-comportamiento es el foco de la academia. Esta composición rompe

con la limitación tradicional de sólo estudiar la innovación tecnológica verde desde la perspectiva de la lógica del comportamiento, y trae la lógica conceptual del sujeto a la perspectiva de la investigación. Diseña el mecanismo de transformación de la innovación tecnológica verde en las industrias manufactureras impulsadas por factores internos y externos, construye un modelo de juego evolutivo de tres partes, fabricación, gobierno y consumidor, y moviliza el software de Matlab para las hacer simulaciones. Así, se revelan los efectos de las regulaciones ambientales con diferentes intensidades sobre la transformación de la innovación tecnológica verde en las industrias manufactureras, para proporcionar una base teórica para que las regulaciones ambientales la guíen.

INTRODUCTION

As a novel mode of technological innovation, not only is green technological innovation a product of the organic integration of sustainable development concept and innovation-driven strategy, but also an originally driving force for adjustment of globally industrial structure and construction of ecological civilization (Guo et al. 2019). The mode of extensive development of traditional manufacturing industries intensifies the contradiction between economic development and environmental protection. Consequently, it is indispensable for manufacturing industries to conduct the transformation of green technological innovation.

Since the concept of green technological innovation was put forward, a sea of scholars have carried out plentiful researches on the types, driving factors and influential effects of green technological innovation.

From perspective of types of green technological innovation, previous studies, according to application objects of technological innovation, started from the behavioral logic of green technological innovation, divided green technological innovation into green product innovation, green process innovation and so on. Furthermore, they researched the types of green technological innovation from the perspective of the object of green technological innovation (Wang et al. 2018). The behavioral consciousness of the subject of green technological innovation conceptual logic has a crucial influence on behavioral choices and implementation effect of green technological innovation. Nevertheless, the existing literature rarely deals with this aspect. Accordingly, it has more critical value to carry out researches on green technological innovation from the coupling perspective of behavioral logic and conceptual logic.

As for the view of the driving factors of green technological innovation, previous studies only considered the impact of internally driving factors, such as the human capital (Yang et al. 2021), technological capabilities and enterprise scales (Su and Li 2021), on green technological innovation, but the negative externalities of green technological innovation to the power of green technological innovation are insufficient, which requires the government (Cai et al. 2020), consumers (Yang and You 2021) and other external factors to encourage and guide green technological innovation. In addition, the demand of consumers for green products could stimulate the R&D investment of manufacturing industries in green technological innovation (Li et al. 2018). However, it is not comprehensive to research the driving mechanism of green technological innovation only considering internally driving factors of green technological innovation and ignoring the environmental regulation and consumers' concepts of environmental protection as the external driving factors. Thus, it is significant to explore the influence of internally and externally driving factors on the transformation of green technological innovation in manufacturing industries.

From the point of the effect of green technological innovation, previous studies utilized dynamic panel data to analyze the impact of environmental regulations on green technology innovation from the perspectives of provincial (Guo and Yang 2020, Guo 2019), prefecture-level (Kuang and Lu 2019, Ye et al. 2018) and industry levels (Xu and Wang 2018, Xu et al. 2020). However, its impact is restricted by the choice of different tools of environmental regulation (Wang et al. 2021). Nevertheless, the existing literature lacks comprehensive and in-depth research on the heterogeneous impact of environmental regulation on green technological innovation. Whereas few scholars mobilize the model of evolutionary game to explore the impact of it. Moreover, the evolution game could fully analyze the situation of mutual constraints of different strategies and

dynamic evolution among participants. In addition, the transformation of green technological innovation in manufacturing industries mainly involves three stakeholders. Among them, manufacturing industries are the main body of the transformation of green technological innovation; the government is the main implementer of environmental regulation, which decreases the negative externality of green technological innovation; and consumers' demand for green products is the end of realizing the value of green technological innovation (Wang and Li et al. 2021). These three are the main actors that enhance green technological innovation. Thus, the existing literature mainly analyze the two-party game among manufacturing industries, the government, and consumers, when applying evolutionary game (Yang and Liu 2017, Li et al. 2021), and few research the three-party stakeholders in green technological innovation at the same time.

In view of this, this paper breaks through limitation of traditional research of green technological innovation only from the behavioral logic and brings the conceptual logic of subjects of green technological innovation into the research perspective. Based on behavioral consciousness of manufacturing subjects, this paper classifies types of green technological innovation, and comprehensively takes the impact of the dual driving factors of green technological innovation in manufacturing into account. The model of tripartite evolutionary game of manufacturing industries, the government, and consumers is constructed. Matlab2020A software is mobilized to simulate and analyze the impact of different types of environmental regulations on the transformation of green technological

innovation of manufacturing industries, to provide targeted countermeasures and suggestions for the government to formulate policies of environmental regulation and promote the transformation of green technology innovation in manufacturing industries.

Research on the mechanism of transformation of green technological innovation in manufacturing industries

The concept and classification of environmental regulation

Environmental regulation refers to the mode of social regulation in which the government, through the formulation of relevant environmental policies and laws, gives play to the role of market mechanism in resource allocation and constrains the behaviors of social and economic subjects to meet the public goals and needs (Qiao, 2021). Its purpose is to reduce the pollution emissions of enterprises, optimize the mode of production and promote sustainable economic development. According to the main body of environmental regulation, it can be divided into three types: command-and-control environmental regulation, market-based incentive environmental regulation and public participation, and the impact on green technology innovation is heterogeneous (Liu and Zhu, 2020). And the comparative analysis of the three types of environmental regulations is shown in **table I**.

TABLE I. COMPARATIVE ANALYSIS OF TYPES OF ENVIRONMENTAL REGULATION.

Types of regulation	Ways of regulation	Subjects	Cost	Environmental benefits	Characteristic
Command-and-control	Sewage discharge permission, standard of pollutant discharge, specify the deadline for governance, etc.	Administrative departments such as the government	Higher	Short term	It draws significant effect but spends high regulatory costs.
Market-based incentive	Emission taxes, environmental subsidies, green-credit policy, pollution rights trading, etc.	Administrative departments such as the government	Higher	Long term	The incentive effect is higher, but the regulation function is not specific, there is spillover lags.
Public participation	Public participation, media supervision, environmental certification, etc.	Government departments, industry associations, communities, etc	Lower	Long term	Enterprises have larger rights of independent choice.

TABLE II. THE CONCEPT AND CLASSIFICATION OF GREEN TECHNOLOGICAL INNOVATION.

Classification	Motivation for innovation	Innovation process	Innovative effect
Class I Green technological innovation	Passive form	Single externality	Resource savings
Class II Green technological innovation	Active form	Dual externality	Friendly environment
Class III Green technological innovation	Actively and passively mixed form	Single and dual externality	Resource savings and friendly environment

The concept and evolutionary trend of the transformation of green technological innovation

The concept of green technology innovation was first put forward by Brawn&Wield (1994). When reducing the dual externalities of traditionally technological innovation on the environment, a system of harmonious and unified environmental technology with economic benefits and sustainable development could be achieved (Wang and Zhang 2018). The theory of planned behavior divides green technological innovation into green technological innovative intention and green technological innovative behavior (Zhang and Whang 2018). The "method of bisection" divides green technology innovation into green product innovation and green process innovation. The "rule of the third" divides green technology innovation into end-treatment technological innovation, green process innovation and green product innovation (Li et al. 2013). The previous studies all started from behavioral logic and divided green technological innovation according to the application objects of technological innovation. Nevertheless, behavioral consciousness of the subject of green technological innovation-conceptual logic has a significant influence on the behavioral choice and implemental effect of green technological innovation. Therefore, in this paper, based on the main body of green technological innovation in the pursuit of environmental performance of active consciousness, and in accordance with the domestic and foreign scholars to measure the two dimensions of standard of sustainable development of "resource conservation" and "environmentally friendly" (Li 2015), green technological innovation can be divided into three categories, and then from the motivation for innovation, process and effect of differences and relationship between the three defined, as shown in **table II**.

According to **table II**, it is of great necessity and significance to discuss the transformation of green technological innovation in accordance with motivation of the behavioral subject's conceptual logic.

Previous studies on green transformation of manufacturing industries believe that the transformation of green technological innovation in manufacturing industries is to enhance the efficiency of resource utilization and achieve sustainable development of resources and environment by means of technological innovation (Li 2011). The transformation of green technological innovation in manufacturing industries in this study refers to the process of gradual transformation from passive—Class I Green technological innovation to active—Class II Green technological innovation. Class III Green technological innovation is a form of short transition. The transformation process of green technological innovation in manufacturing industries is shown in **figure 1**.

As can be seen from **figure 1**, manufacturing industries execute Class I Green technological innovation may lack the consciousness of active pursuit of environmental performance. In the process of continuous development, they gradually transform into Class III Green technological innovation and eventually develop into Class II Green technological innovation. The evolution of the transformation

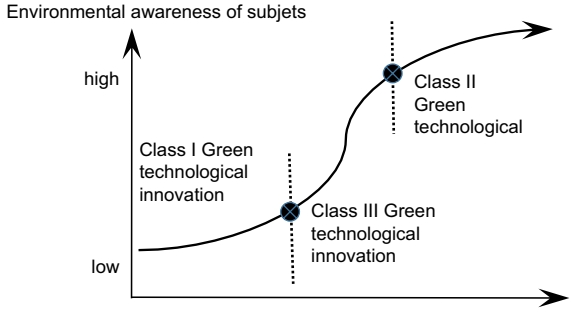

Fig. 1. The process chart of transformation of green technological innovation in manufacturing industries.

of green technological innovation in manufacturing industries researched in this paper is mainly aimed at the transformation from Class I to Class II Green technological innovation.

The role mechanism of transformation of green technological innovation in manufacturing industries

Green technology innovation is the internally driving force in the development of green manufacturing (Hou et al. 2020). Environmental awareness of consumers is a critical condition for guiding the transformation of green technological innovation in manufacturing (Torani et al. 2016). While reducing energy consumption and promoting economic benefits (Melander et al. 2019), green technology in manufacturing industries will be accompanied by risks such as high cost, long cycle and uncertainty (Qin and Sha 2017). The negative externalities of green technological innovation (Wang and Li 2020) and consumers' lack of environmental awareness make it difficult for the government's environmental regulation to develop efficiently in the long term (Axsen et al. 2017). Thus, driven by such dual factors, it is particularly indispensable for the government to adopt measures of environmental regulation to supervise them. The mechanism of action among manufacturing, government and consumers is shown in figure 2.

As can be seen from **figure 2**, the main actors of transformation of green technological innovation in manufacturing industries are the manufacturing industries, the government, and consumers. The regulatory measures available to the government are command-and-control, market-based incentive, and public participation. Command-and-control environmental regulation is to levy corresponding pollution taxes on Class I Green technological innovation in manufacturing industries through administrative means, and the manufacturing industries will make discretionary decisions based on its own development (Tao et al. 2021). Furthermore, the method of implementing market-based incentive environmental regulation is that the government encourages the manufacturing industries to conduct Class II Green technological innovation through green subsidies, and at the same time makes innovative compensation for consumers supervision, so as to promote the transformation of green technological innovation in manufacturing industries, which would achieve the purpose of reducing environmental pollution (Wu et al. 2020). The realization of public participation environmental regulation mainly depends on the consciousness of environmental protection of the public. As the executor of environmental regulation, on the one hand, the government ought to strengthen education of knowledge of environmental protection for consumers to supervise manufacturing industries in green technological innovation; on the other, the manufacturing industries are supposed to be stimulated to actively pursue green technological innovation to enhance the efficiency of the environmental improvement.

Analysis of evolutionary game of the manufacturing industries, the government, and consumers under environmental regulation

Model hypotheses

In an environment where other constraints are not considered, manufacturing industries, the government

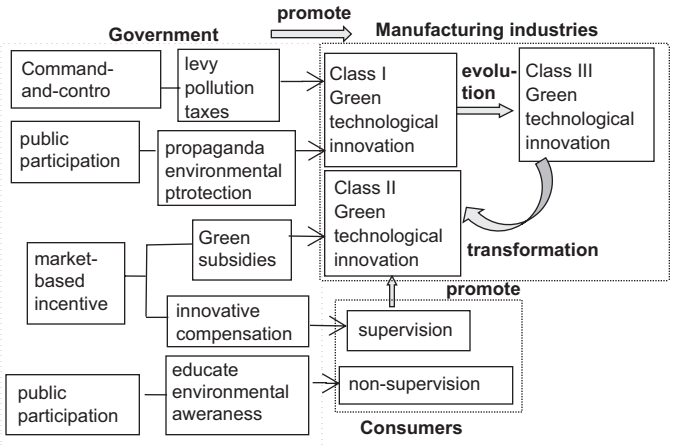

Fig. 2. The chart of impact mechanism of transformation of green technological innovation in manufacturing industries under environmental regulation.

and consumers will be as a complete system. At the same time, the three subjects in the system are limited rationality. Due to the difference in the goals pursued by the game, the information and resources they have mastered are asymmetrical, which makes them impossible to find optimal strategies at the beginning. Instead, they constantly learn and improve during the game, and ultimately achieve the maximization of their own interests. Supposing the strategies of manufacturing industries are Class I Green technological innovation and Class II Green technological innovation; the government is regulation and non-regulation; consumers are supervision and non-supervision. The probability of manufacturing industries for Class II Green technological innovation is x; the probability of government regulation is y; the probability of consumers to supervise is z. The model is assumed as follows:

First, environmental regulation is divided into three types, such as levy pollution tax, green subsidies, and propaganda environmental protection. The government levied the pollution tax fees on Class I Green technological innovation in manufacturing industries are αA; the government's incentives of green subsidies for Class II Green technological innovation are βB, and of innovative compensation for consumers who supervise the manufacturing industries are ωK; the government's cost of environmental protection of publicity for Class I Green technological innovation is γJ, and the government consumes the cost of environmental awareness education for consumers who do not supervise the manufacturing industry is δM.

Second, when the manufacturing industries conduct Class I Green technological innovation and Class II Green technological innovation to produce, their basic benefits are severally R_{11} and R_{12} ($R_{11}<R_{12}$), and the costs given are C_{11} and C_{12}, respectively. When the manufacturing industries implement Class II Green technological innovation, consumers supervision will increase the credibility of the manufacturing, enabling them to obtain additional benefits π.

Third, when the government doesn't supervise the manufacturing, the fundamentally financial revenue is R_2. To achieve economic sustainable development, the government puts into lots of resources for monitoring, and the cost required is C_2. The manufacturing industries that conduct Class II Green technological innovation will increase the green benefits of society, and the increase in amounts is Δr_1. The government has supported mobilize green technology to improve the awareness of public participation in environmental protection. At this time, the government supports the manufacturing for Class II Green technological innovation and will have invisible benefits Δr_2. The government does not regulate the manufacturing industries for Class I Green technological innovation, which will result in the loss of reputation and the amount is $-\Delta v$.

Forth, the manufacturing industries that execute Class II Green technological innovation enable the public to obtain environmental income R_3. Conversely, it will contribute to losses to the public and the amount of loss is L. When the government regulates and doesn't regulate, the public's costs of supervision are C_{31} and C_{32} ($C_{31} < C_{32}$), respectively.

Payoff matrix of tripartite evolutionary game model

According to the above basic hypotheses, this article constructs the payoff matrix of the tripartite evolutionary game, as shown in **table III**.

Establishing the replicated dynamic equation

When manufacturing industries conduct Class I Green innovation, its expected return is:

$$\begin{aligned} &E_{11} = yz(R_{12} - C_{12} + \beta B + \pi) + \\ &y(1-z)(R_{12} - C_{12} + \beta B) + (1-y)z(R_{12} - C_{12} + \pi) + \\ &(1-y)(1-z)(R_{12} - C_{12}) \end{aligned} \tag{1}$$

When manufacturing industries implement Class II Green innovation, its expected return is:

$$\begin{aligned} &E_{12} = yz(R_{11} - C_{11} - \alpha A) + \\ &y(1-z)(R_{11} - C_{11} - \alpha A) + (1-y)z(R_{11} - C_{11}) + \\ &(1-y)(1-z)(R_{11} - C_{11}) \end{aligned} \tag{2}$$

Its average excepted return is:

$$E_1 = x\,E_{11} + (1-x)E_{12} \tag{3}$$

The replicated dynamic equation for the manufacturing industries in conducting Class II Green technological innovation is:

$$\begin{aligned} &F(x) = \frac{dx}{dt} = x(E_{11} - E_1) \\ &= x(1-x)[y(\beta B + \alpha A) + \\ &z\pi + C_{11} - C_{12} - R_{11} + R_{12}] \end{aligned} \tag{4}$$

Similarly, the replicated dynamic equation for the government regulation is:

$$\begin{aligned} &F(y) = \frac{dy}{dt} = y(E_{21} - E_2) = \\ &y(1-y)[x(\gamma J - \alpha A - \beta B - \Delta v) + z(\delta M - \omega K) + \\ &\alpha A - \gamma J - \delta M - C_2 + \Delta v + \Delta r_2] \end{aligned} \tag{5}$$

TABLE III. PAYOFF MATRIX OF THE TRIPARTITE EVOLUTIONARY GAME.

Manufacturing industries	Goverment	Consumers (supervision) z	Consumers (non-supervision) $1-z$
Class II Green technological innovation x	Regulation y	$R_{12}-C_{12}+\beta B+\pi$	$R_{12}-C_{12}+\beta B$
		$R_2+\Delta r_1-C_2-\beta B-\omega K+\Delta r_2$	$R_2+\Delta r_1-C_2-\beta B-\delta M+\Delta r_2$
		$R_3-C_{31}+\omega K$	R_3
	non-regulation $1-y$	$R_{12}-C_{12}+\pi$	$R_{12}-C_{12}$
		$R_2+\Delta r_1$	$R_2+\Delta r_1$
		R_3-C_{32}	R_3
Class I Green technological Innovation $1-x$	Regulation y	$R_{11}-C_{11}+\alpha A$	$R_{11}-C_{11}+\alpha A$
		$R_2-C_2+\alpha A-\gamma J-\omega K+\Delta r_2$	$R_2-C_2+\alpha A-\gamma J-\delta M+\Delta r_2$
		$\omega K-C_{31}$	$-L$
	non-regulation $1-y$	$R_{11}-C_{11}$	$R_{11}-C_{11}$
		$R_2-\Delta v$	$R_2-\Delta v$
		$-C_{32}$	$-L$

The replicated dynamic equation for consumers supervising is:

$$F(z)=\frac{dz}{dt}=z(1-z) \quad (6)$$
$$[-xL+y(\omega K-C_{31}+C_{32})+L-C_{32}]$$

Analysis of the evolutionary stability

Let $F(X_2)=0$, $F(y)=0$, $F(z)=0$, we can obtain eight equilibrium points, such as $E_1(0,0,0)$, $E_2(0,1,0)$, $E_3(0,0,1)$, $E_4(1,0,0)$, $E_5(1,1,0)$, $E_6(1,0,1)$, $E_7(0,1,1)$, $E_8(1,1,1)$. According to the study of Friedman, the solution of evolutionary equilibrium of the replicated dynamic equation is obtained by the analysis from local stability of Jacobion matrix of the system. Then partial derivatives of F (x_2), F (y), F (z) could acquire Jacobian matrix.

$$J=\begin{bmatrix} \frac{\partial F(x_2)}{\partial x_2} & \frac{\partial F(x_2)}{\partial y} & \frac{\partial F(x_2)}{\partial z} \\ \frac{\partial F(y)}{\partial x_2} & \frac{\partial F(y)}{\partial y} & \frac{\partial F(y)}{\partial z} \\ \frac{\partial F(z)}{\partial x_2} & \frac{\partial F(z)}{\partial y} & \frac{\partial F(z)}{\partial z} \end{bmatrix}=\begin{bmatrix} A_{11} & A_{12} & A_{13} \\ A_{21} & A_{22} & A_{23} \\ A_{31} & A_{32} & A_{33} \end{bmatrix} \quad (7)$$

$$A_{11}=(1-2x)[y(\beta B+\alpha A)+ z\pi+C_{11}-C_{12}-R_{11}+R_{12}] \quad (8)$$

$$A_{11}=(1-2x)[y(\beta B+\alpha A)+ z\pi+C_{11}-C_{12}-R_{11}+R_{12}] \quad (9)$$

$$A_{13}=x(1-x)\pi \quad (10)$$

$$A_{21}=y(1-y)(\gamma J-\alpha A-\beta B-\Delta v) \quad (11)$$

$$A_{22}=(1-2y)[x(\gamma J-\alpha A-\beta B-\Delta v)+z(\delta M-\omega K) +\alpha A-\gamma J-\delta M-C_2+\Delta v+\Delta r_2] \quad (12)$$

$$A_{23}=y(1-y)(\delta M-\omega K) \quad (13)$$

$$A_{31}=z(1-z)(-L) \quad (14)$$

$$A_{32}=z(1-z)(\omega K-C_{31}+C_{32}) \quad (15)$$

$$A_{33}=(1-2z)[-xL+y(\omega K-C_{31}+C_{32})+L-C_{32}] \quad (16)$$

According to the evolutionary game theory, stable points of the replicated dynamic equation that meets eigen value of Jacques matrix are negative conditions. Thus, these points are brought into Jacobian matrix, which acquires results of asymptotic stability of the evolution game, as shown in **table IV**.

It can be seen from **table IV**, in the replication dynamic system of the three-way evolution game between the government, manufacturing, and consumers, that E_1 (0,0,0) E_2 (0,1,0), E_3 (0,0,1), E_4

TABLE IV. ANALYSIS OF THE STABILITY OF EQUILIBRIUM SOLUTION OF EVOLUTIONARY GAME.

Partial equation	Eigen value	Condition for stability	Stability
E_1 (0,0,0)	$C_{11} - C_{12} - R_{11} + R_{12}$ $\alpha A - \gamma J - \delta M - C_2 + \Delta v + \Delta r_2$ $S - C_{32}$	$C_{11} - C_{12} - R_{11} + R_{12}$ $\alpha A - \gamma J - \delta M < C_2 - \Delta v - \Delta r_2$ $S < C_{32}$	The asymptotically stable point
E_2 (0,1,0)	$\beta B + \alpha A + C_{11} - C_{12}$ $R_{11} + R_{12}$ $\delta M - \alpha A + \gamma J + C_2 - \Delta v - \Delta r_2$ $\omega K - C_{31} + S$	$\beta B + \alpha A < -C_{11} + C_{12} + R_{11} - R_{12}$ $\delta M - \alpha A + \gamma J < -C_2 + \Delta v + \Delta r_2$ $\omega K + S < C_{31}$	The asymptotically stable point
E_3 (0,0,1)	$\pi + C_{11} - C_{12} - R_{11} + R_{12}$ $\alpha A - \gamma J - \omega K - C_2 + \Delta v + \Delta r_2$ $C_{32} - S$	$C_{11} - C_{12} + \pi < R_{11} - R_{12}$ $\alpha A - \gamma J - \omega K < C_2 - \Delta v - \Delta r_2$ $C_{32} < S$	The asymptotically stable point
E_4 (1,0,0)	$-C_{11} + C_{12} + R_{11} - R_{12}$ $-\beta B - \delta M - C_2 + \Delta r_2$ $-C_{32}$	$R_{11} - R_{12} < C_{11} - C_{12}$ $-\beta B - \delta M < C_2 - \Delta r_2$	The asymptotically stable point
E_5 (1,1,0)	$R_{11} - R_{12} - C_{11} + C_{12} - \alpha A - \beta B$ $\beta B + \delta M + C_2 - \Delta r_2$ $\omega K - C_{31}$	$R_{11} - R_{12} - C_{11} + C_{12} < \alpha A + \beta B$ $\beta B + \delta M < C_2 + \Delta r_2$ $\omega K < C_{31}$	The asymptotically stable point
E_6 (1,0,1)	$-\pi - C_{11} + C_{12} + R_{11} - R_{12}$ $-\beta B - \omega K - C_2 + \Delta r_2$ C_{32}	–	The unstable point
E_7 (0,1,1)	$\beta B + \alpha A - C_{11} - C_{12} - R_{11} + R_{12}$ $\omega K - \alpha A + \gamma J + C_2 - \Delta v - \Delta r_2$ $\omega K - S + C_{31}$	$\beta B + \alpha A + \pi < R_{11} - R_{12} - C_{11} + C_{12}$ $\omega K - \alpha A + \gamma J < \Delta v + \Delta r_2 - C_2$ $-\omega K < S - C_{31}$	The asymptotically stable point
E_8 (1,1,1)	$-\beta B - \alpha A - \pi - C_{11} + C_{12} + R_{11} - R_{12}$ $\beta B + \omega K + C_2 - \Delta r_2$ $-\omega K + C_{31}$	$R_{11} - R_{12} - C_{11} + C_{12} - \pi < \beta B + \alpha A$ $\beta B + \omega K < \Delta r_2 - C_2$ $C_{31} < \omega K$	The asymptotically stable point

(1,0,0), E_5 (1,1,0), E_7(0,1,1) and E_8 (1,1,1) are stable points. During the development of the manufacturing economy, if the government does not carry out strict environmental regulations and consumers don't supervise, manufacturing industries only rely on the change of environmental awareness itself to drive transformation of green technological innovation, which will lead to slowly green development of the manufacturing. Thus, problems of resource shortage and environmental pollution cannot be fundamentally resolved. Therefore, the environmental regulation of the government and the supervision of the public will have active effects on the initiative of the manufacturing industry. Through the above analysis, the dominant strategy of the tripartite game is "Class II Green technology innovation, regulation, supervision". The stable conditions of the strategy are that the difference between returns and cost of Class I Green technology innovation and Class II Green technology innovation of manufacturing is less than taxes for Class I Green technology innovation plus green subsidies for Class II Green technology innovation; the government's subsidies for manufacturing and consumers are less than the difference between invisible income and regulation costs of government regulation; the public's supervisory costs are smaller than the government's compensation for consumers.

Analysis on the tripartite equilibrium strategy of manufacturing industries, the government and consumers

Equilibrium strategies of the manufacturing industries

From formula (4), when the condition $y = \frac{R_{11} - R_{12} - C_{11} + C_{12} - z\pi}{\beta B + \alpha A}$ is satisfied, it can be seen that $F(x) \equiv 0$. Any probability "Class II Green technological innovation" strategy adopted by the manufacturing industries is a stable strategy, in which the probability of the strategy is not affected by time changes. Consequently, all strategies of manufacturing industries are in equilibrium state. The replicative dynamic phase image of strategical selection of manufacturing industries is shown in **figure 3**.

When the condition $y \neq \frac{R_{11} - R_{12} - C_{11} + C_{12} - z\pi}{\beta B + \alpha A}$ is satisfied, let $F(x) = 0$, we can get two stable points $x = 0$,

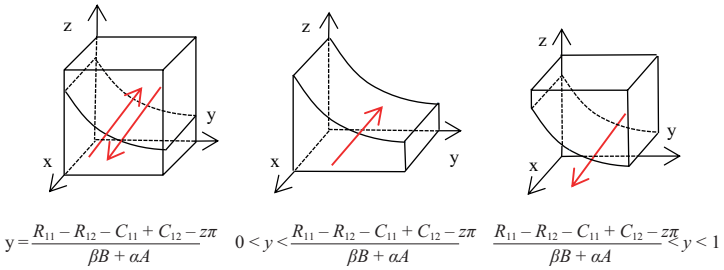

Fig. 3. The phase image of manufacturing industries.

$x = 1$. Therefore, the discussion is divided into two situations:

Case 1: When the condition $0 < y < \frac{R_{11}-R_{12}-C_{11}+C_{12}-z\pi}{\beta B+\alpha A}$ is satisfied, $F'(x = 0) < 0$, $F'(x = 1) > 0$, so $x = 0$ is a stable strategy. At this point, manufacturing industries conduct Class I Green technological innovation.

Case 2: When the condition $\frac{R_{11}-R_{12}-C_{11}+C_{12}-z\pi}{\beta B+\alpha A} < y < 1$ is satisfied, $F'(x = 0) > 0$, $F'(x = 1) < 0$, so $x = 1$ is a stable strategy. And they execute Class II Green technological innovation.

Equilibrium strategies of the government

From formula (5), when the condition: $z=\frac{\gamma J-\alpha A+\delta M+C_2-\Delta v-\Delta r_2-x(\gamma J-\alpha A-\beta B-\Delta v)}{\delta M-\omega K}(z=z^*)$ is satisfied, it can be seen that $F(y) \equiv 0$. Any probability "regulation" strategy adopted by the government is a stable strategy, in which the probability of the strategy is not affected by time changes. Consequently, all strategies of the government are in equilibrium state. The replicative dynamic phase image of strategical selection of the government is shown in **figure 4**.

When the condition: $0<z<\frac{\gamma J-\alpha A+\delta M+C_2-\Delta v-\Delta r_2-x(\gamma J-\alpha A-\beta B-\Delta v)}{\delta M-\omega K}(0<z<z^*)$ is satisfied, let $F(y) = 0$, we can get two stable points $y = 0$, $y = 1$. Therefore, the discussion is divided into two situations:

Case 1: When the condition: $0<z<\frac{\gamma J-\alpha A+\delta M+C_2-\Delta v-\Delta r_2-x(\gamma J-\alpha A-\beta B-\Delta v)}{\delta M-\omega K}(0<z<z^*)$ is satisfied, $F'(y = 0) < 0$, $F'(x = 1) > 0$, so $y = 0$ is a stable strategy. At this point, the government regulates.

Case 2: When the condition: $\frac{\gamma J-\alpha A+\delta M+C_2-\Delta v-\Delta r_2-x(\gamma J-\alpha A-\beta B-\Delta v)}{\delta M-\omega K}<z<1(z^*<z<1)$ is satisfied, $F'(y = 0) > 0$, $F'(x = 1) < 0$, so $y = 1$ is a stable strategy. And it does not regulate.

Equilibrium strategies of consumers

From formula (6), when the condition $y \neq \frac{xL-L+C_{32}}{\omega K-C_{31}+C_{32}}$ is satisfied, it can be seen that $F(z) \equiv 0$. Any probability "supervision" strategy adopted by consumers is a stable strategy, in which the probability of the strategy is not affected by time changes. Consequently, all strategies of consumers are in equilibrium state. The replicative dynamic phase image of strategical selection of consumers is shown in **figure 5**.

When the condition $y \neq \frac{xL-L+C_{32}}{\omega K-C_{31}+C_{32}}$ is satisfied, let $F(z) = 0$, we can get two stable points $z = 0$, $z = 1$. Therefore, the discussion is divided into two situations:

Case 1: When the condition $0 < y < \frac{xL-L+C_{32}}{\omega K-C_{31}+C_{32}}$ is satisfied, $F'(z = 0) < 0$, $F'(z = 1) > 0$, so $z = 0$ is a stable strategy. At this point, consumers supervise.

Case 2: When the condition $\frac{xL-L+C_{32}}{\omega K-C_{31}+C_{32}}<y<1$ is satisfied, $F'(z = 0) > 0$, $F'(z = 1) < 0$, so $z = 1$ is a stable strategy. And they don't supervise.

Simulation study on transformation of green technological innovation in manufacturing industries under environmental regulation

In the tripartite evolutionary game, the change of each parameter will affect the choice of equilibrium

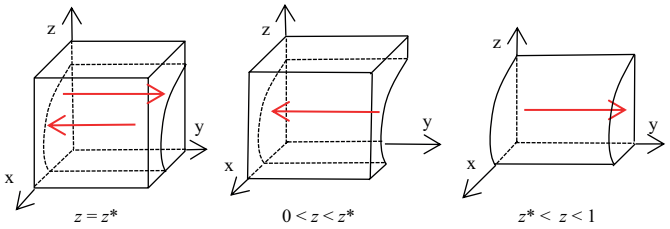

Fig. 4. The phase image of the government.

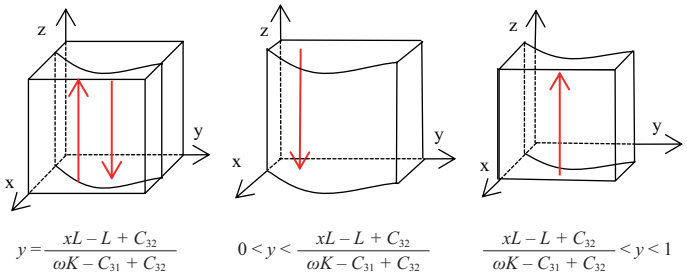

Fig. 5. The phase image of consumers.

strategies of the main body, and then impress the change of the evolutionary state. To analyze the influence of different types of environmental regulation and its intensity on the evolutionary trajectory of the transformation of green technological innovation in manufacturing industries, Matlab2020A was utilized to simulate and analyze the evolutionary equilibrium state of the tripartite evolutionary game model. At the beginning, the probability of setting the behavior choices of manufacturing industry, government and consumers is 0.5, and the size of cycle step is 0.2. The direction of systematic evolution is observed, and the simulation conclusions are shown in **figure 6**.

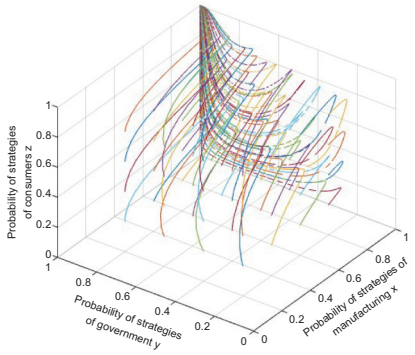

Fig. 6. The trend of tripartite dynamic evolution.

The impact of command-and-control environmental regulation on system evolution

When the intensity of pollution taxes levied by the government on Class II Green technological innovation in manufacturing industries is 0.2, 0.5 and 0.8, respectively, the simulation consequences are shown in **figure 7**. The three parties of the game all choose "Class II Green technological innovation, regulation, and supervision" as the final strategy.

As can be revealed from **figure 7a**, the levy of pollution taxes could enhance Class II Green technological innovation in manufacturing industries, and with the increasing intensity of the levy of pollution taxes, the manufacturing industries will accelerate the speed of the transformation of green technological innovation. From **figure 7c**, the strikingly high intensity of pollution taxes will promote the supervision of consumers on the green technological innovation in manufacturing industries.

As for the manufacturing industries, with the strengthening of the government's pollution taxes, they, under the pressure of government punishment, could accelerate the transformation of green technological innovation and continuously optimize the natural resources. When the government's

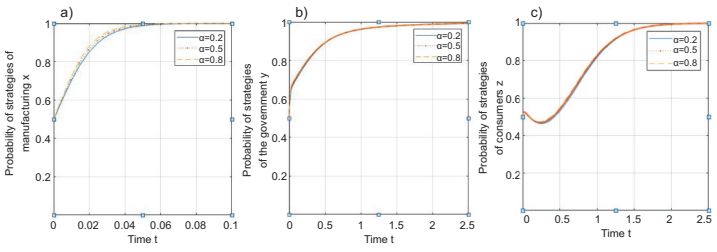

Fig. 7. The evolutionary trend of levying pollution taxes under the intensity of different enforcement. a) simulation results of manufacturing strategies; b) simulation results of the government; c) simulation results; of consumers.

environmental regulation continues to reinforce, consumers, deeply influenced by the government, will consciously strengthen the supervision of manufacturing industries.

Conclusion 1: The government levy pollution taxes will enhance the transformation of green technological innovation in manufacturing industries and accelerate the speed of it.

Conclusion 2: The government levied pollution taxes on manufacturing would encourage consumers surveillance.

The impact of market-based incentive environmental regulation on system evolution

The measures of market-based incentive environmental regulation adopted by the government mainly include incentive of green subsidies for Class II Green technological innovation and innovative compensation for consumers who supervise behaviors of green technological innovation in the manufacturing industries.

The impact of the incentive of green subsidies on system evolution

When the intensity of the government's green subsidies for Class II Green technological innovation is 0.2, 0.5 and 0.8, respectively, the simulation consequences are shown in **figure 8**.

From **figure 8a**, green subsidies have positive effects on green technological innovation in the manufacturing industries; from **figure 8a** and **8b**, when the intensity of green subsidies is 0.8, it has the strongest improvement on the transformation of green technology innovation, but it restrains the regulation of the government and the supervision of consumers; from **figure 8c**, the supervision of consumers is restricted with the strengthening of the degree of green subsidies.

Green subsidies, as a way of compensating for innovation, favor manufacturers diminish the cost of research and development of green technological innovation. Whereas, for the government, green subsidies will increase the expenditure of financial funds, which makes the pressure of environmental regulation suddenly strengthens. Hence, moderately green subsidies will enhance the market-oriented incentive environmental regulation, while green subsidies of high intensity would force the government to abandon environmental regulations. For consumers, with the improvement of the transformation of green technological innovation in the manufacturing industries, the ecological environment has been improved. To save supervision costs and avoid unnecessary waste, consumers gradually relax their supervision on the manufacturing industries.

Conclusion 3: The government's incentive means of green subsidies will enhance the transformation of green technology innovation in manufacturing industries.

Conclusion 4: The high intensity of green subsidies speeds up the transformation of green technological innovation in the manufacturing industries, but it restrains the government's market-based incentive environmental regulation and consumers' supervision.

The impact of the incentive of innovative compensation on system evolution

When the incentive intensity of government's innovative compensation to consumers is 0.2, 0.5 and 0.8, respectively, the simulation conclusions are shown in **figure 9**.

From **figure 9a**, the government's innovation compensation could positively promote the manufacturing industries to conduct Class II Green technological innovation; from **figure 9c**, when the intensity of innovative compensation is 0.2, consumers' supervision of Class II Green technological innovation will be inhibited. And when it is 0.5, consumers' supervision will be improved.

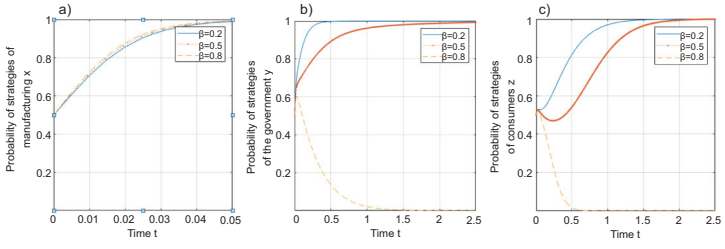

Fig. 8. The evolutionary trend of the incentive of green subsidies under the intensity of different enforcement. a) simulation results of manufacturing strategies; b) simulation results of the government; c) simulation results of consumers.

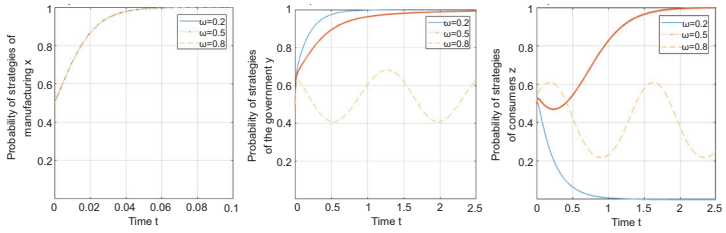

Fig. 9. The evolutionary trend of the incentive of innovative compensation under the intensity of different enforcement. a) simulation results of manufacturing strategies; b) simulation results of the government; c simulation results of consumers.

Innovative compensation could assist consumers to reduce the cost of supervision on the manufacturing industry and enhance consumers' enthusiasm to purchase green products, which could boost the market share of green products, and thus enhance the transformation of green technological innovation in the manufacturing industries. Nevertheless, for consumers, from the perspective of benefit maximization, low intensity of innovative compensation is not enough to make up for the cost of public supervision of green technology innovation in manufacturing industries, which makes consumers give up supervision. Appropriately innovative compensation will favor consumers to decrease the supervision cost, so that consumers pay less cost and enjoy the intangible benefits brought by the environmental improvement, which would strengthen consumers' supervision.

Conclusion 5: Low intensity of innovative compensation restrain consumers' supervision of the transformation of green technological innovation in manufacturing industries, while moderately innovative compensation will promote it.

Conclusion 6: The government's innovative compensation to consumers will improve the transformation of green technological innovation in manufacturing industries.

The impact of public participation environmental regulation on systematical evolution

The measures of public participation environmental regulation adopted by the government mainly include publicity of environmental protection for Class I Green technological innovation in manufacturing industries and the education of environmental awareness for consumers who do not supervise the behavior of green technological innovation of manufacturing industries.

The impact of the publicity of environmental protection on systematical evolution

When the intensity of publicity of environmental protection by the government on manufacturing industries is 0.2, 0.5 and 0.8, respectively, the simulation conclusions are shown in **figure 10**. The three parties of the game all choose "Class II Green technological innovation, regulation, and supervision" as the final strategy.

From **figure 10a**, the publicity of environmental protection is actively promoting Class II Green technological innovation in the manufacturing industries. However, with the deepening of the government's publicity of environmental protection, the strategical choices of manufacturing industries are not sensitive

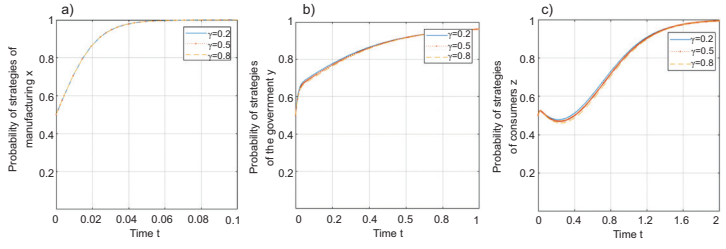

Fig. 10. The evolutionary trend of the publicity of environmental protection under the intensity of different enforcement. a) simulation results of manufacturing strategies; b) simulation results of the government; c) simulation results of consumers.

to the intensity of it; from **figure 10c**, the government's strengthening of publicity on environmental protection restrains consumers' supervision of the manufacturing industries.

This is because, although the government's way of publicity of environmental protection enhances the enthusiasm of manufacturing industries that promote the transformation of green technological innovation, the mode of development of "high consumption, high input and high pollution" in the manufacturing industries has been deeply rooted. Consequently, environmental propaganda alone doesn't solve matters the long-term development of manufacturing industries. Accordingly, the high intensity of propaganda of environmental protection cannot accelerate the speed of the transformation of green technological innovation in the manufacturing industries. In addition, the government's efforts to promote environmental protection have convinced consumers that the government's regulation of manufacturing will be able to have a positive effect. Thus, to save costs, consumers will diminish the behavior of supervision.

Conclusion 7: The government's publicity of environmental protection to manufacturing industries will strengthen its transformation of green technological innovation, yet it doesn't accelerate the speed of it.

Conclusion 8: The intensification of government publicity on environmental protection in manufacturing industries gradually restricts consumers' supervision.

The impact of the education of environmental awareness on systematical evolution

When the intensity of the education of environmental awareness by the government on manufacturing industries is 0.2, 0.5 and 0.8, respectively, the simulation conclusions are shown in figure 11.

From **figure 11a**, the education of environmental awareness enhances the transformation of green technological innovation in the manufacturing industries; from **figure 11b**, when the intensity of it is 0.8, the government regulation will be restricted. And when the intensity of it is 0.2, the government regulation will be promoted; from **figure 11c**, when the intensity of it is 0.8, consumers' supervision will be restrained. At the same time, when the intensity of it is 0.2, consumers' supervision will be improved.

Consumer supervision will incur costs. Furthermore, the government carries out the education of environmental awareness to promote the transformation of green technological innovation in manufacturing industries. Part of the input cost of Class II green technological innovation in manufacturing industries will be transferred to consumers. Currently, the government continues to strengthen the intensity of environmental education, which extraordinarily improves the cost of consumers and inhibit the supervision of consumers. In addition, for the government, because of asymmetric information contributes to excessive government's education of environmental consciousness, which makes the government's environmental costs continue to increase. Yet manufacturing can't speed up the rate of the transformation of green technological innovation, and the supervision of consumers is in a passive state. Thus, it will restrain the behavior of government's environmental regulation.

Conclusion 9: The government's education of environmental awareness to consumers will enhance the transformation of green technological innovation in the manufacturing industries.

Conclusion 10: Low intensity of environmental education will reinforce the government regulation and consumers' supervision; high intensity of environmental education would restrain it.

The implementing countermeasures of transformation of green technological innovation in manufacturing industries

Based on the analysis of model and simulation conclusions, to enhance transformation of green

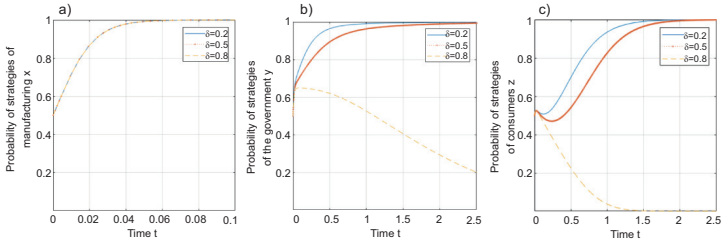

Fig. 11. The evolutionary trend of the publicity of environmental protection under the intensity of different enforcement. a) simulation results of manufacturing strategies; b) simulation results of the government; c) simulation results of consumers.

technological innovation in manufacturing industries, this paper puts forward targeted countermeasures and suggestions from the three levels of the government, manufacturing industries and consumers.

Government level

The government guides the transformation of green technological innovation in manufacturing industries from three perspectives:

1. Improve the system for collecting taxes and fees

First, strengthen the cooperation between environmental protection and tax authorities, optimize the mobilization of resources. In addition, implement differential tax rates. We could set a unified national tax rate, which will fluctuate within a reasonable range but not exceed the prescribed limit. Finally, a strict level certification system of green technological innovation should be established to divide the responsibilities of manufacturing industries with different pollution levels, so that it can efficiently manage the green technology research and development process.

2. Enhance the mechanism of green subsidies

Starting from the market demand of green products, the government ought to decrease unnecessary costs in the process of research and development of green technology through various measures such as green subsidies and loan interest discounts. At the same time, in order to prevent the inhibiting effect for the high-intensity mechanism of green subsidies, it is supposed to set up a perfect system of fund subsidies and post-supervision, from releasing funds for environmental protection to specifically use to carry out a comprehensive audit. If it is found that manufacturing industries have reduced the R&D of green technologies due to the highly green subsidies, these subsidies ought to be withdrawn.

3. Strengthen the concepts of public supervision

The government ought to take fewer intensive measures to strengthen the public's environmental awareness. For instance, it mainly relies on official government platforms, relies more on online marketing, and conducts publicity through low intensity means such as public service advertisements and movies to strengthen public awareness education.

Manufacturing industries level

The manufacturing industries implement the concept of green development from three aspects:

1. Construction of the research and development system of Class II Green technological innovation

First, manufacturing industries itself should formulate strategies of research and development, reasonably deploy its content, and efficiently mobilize its funds. Secondly, we ought to strictly supervise the application of green technology in the production process, adopt green and efficient production methods, rationally allocate existing resources, and decrease resource consumption. Finally, promote the level of green technological innovation, carry out intelligent process, produce competitive green products, which improves the market share and product profits of manufacturing industries.

2. Cultivation of the compound talents of green technological innovation

To begin with, manufacturing industries will introduce advanced technologies and high-quality talents to enhance its capabilities of research and development. Furthermore, it becomes necessary to accelerate the breakthrough of it in key technologies, establish appropriately incentive mechanism of equity for critically technical talents, reduce personnel turnover, and provide the guarantee for the transformation of green technological innovation in manufacturing industries. Eventually, strengthen the interaction with universities. By sending industrial employees to universities for study and exchange, we could strengthen knowledge sharing, improve R&D efficiency, and the transformation of green technological innovation in manufacturing industries.

Establishment of a platform for consumer participation

Through constructing the feedback platform of consumers' information, consumers put forward effective suggestions on the research and development of green products in manufacturing industries after using green products, and even participate in the research and development process of new products, which effectively supervises the transformation of green technological innovation in manufacturing industries.

Consumers level

As the main body of the market, consumers' concepts of environmental protection are crucial to the improvement of the ecological environment. Hence, the transformation of green technological innovation in manufacturing industries could be accelerated from the following two levels:

1. Developing a sense of ownership

On the one hand, consumers ought to actively exercise the rights and obligations of environmental protection and put forward suggestions on the implementation of environmental protection policies and the process of environmental law enforcement by relevant government departments. On the other hand, consumers also actively supervise the production and management process of the green products of manufacturing industries, report fake and shoddy green products, for providing a guarantee for the healthy and stable development of the market of green products.

2. Fostering concepts of green consumption

Consumers are supposed to play the role of monetary votes through purchasing rights and cast them into green and safe food and environment-friendly and energy-saving products. Besides, they could affect the environmental performance of manufacturing industries through their purchase behavior, to promote the overall transformation of socially consumption environment to "green consumption". This will promote integrated development of green consumption and the transformation of green technological innovation in manufacturing industries.

CONCLUSIONS

Based on the coupling perspective of behavioral logic and conceptual logic, this paper discusses the influence of internally driving factors (subjective will of innovative subject) and externally driving factors (environmental regulation and concepts of consumers' environmental protection) on green technological innovation in manufacturing industries, breaking through the limitation of traditional research only from the perspective of behavioral logic. In addition, green technological innovation is divided into three types: Class I, II and III, and the mechanism of internally and externally driving factors on the transformation of green technological innovation in manufacturing industries is analyzed, and then the three-party evolutionary game model of manufacturing-government-consumer is constructed. Furthermore, the research divides environmental regulation into three types: command-and-control, market-based incentive, and public participation. Among them, command-and-control environmental regulations impose pollution taxes α on Class I Green technological innovation in manufacturing industries; the based-market incentive environmental regulations are the incentive of green subsidies β for Class II green technological innovation in manufacturing industries and the innovative compensation for consumers ω who supervise green technological innovation in manufacturing industries; public participation environmental regulations mainly include the publicity of environmental protection γ for Class Green technological innovation in manufacturing industries and the education of environmental awareness δ for consumers who do not supervise green technological innovation of manufacturing industries. In the three-party evolutionary game, the change of each parameter will affect the equilibrium strategies of the three-party of game subjects. Therefore, this research mobilizes Matlab2020a software to discuss the evolutionary trend of them under different intensities (0.2, 0.5, 0.8). The conclusions demonstrate that:

1. For manufacturing industries, three types of environmental regulation (α, β, γ, ω and δ) will positively promote the transformation of green technological innovation in manufacturing industries under any intensity. Among them, the high intensity of imposing pollution taxes α and the incentive of green subsidies β will accelerate the speed of it.

2. For the government, high levels of the incentive of green subsidies β and the education of environmental awareness δ will restrict the government's environmental regulation, instead, other factors will improve it.

For consumers, high intensity of the incentive of green subsidies β, high intensity of publicity of environmental protection γ, low intensity of the innovative compensation for consumers ω and high intensity of the education of environmental awareness δ will restrain consumers' supervision of the transformation of green technological innovation in manufacturing industries; any intensity of imposing pollution taxes α, moderate intensity of the innovative compensation for consumers ω and low intensity of the education of environmental awareness δ will enhance it.

In addition, this article also has deficiencies: when utilizing evolutionary game theory to research, while considering the dynamics of the system, due to the limitations of existing research level, it lacks Class I and II Green technology innovation in manufacturing of empirical data. Therefore, numerical simulation rather than empirical data analysis is adopted in the game simulation of the behavior of the three parties. In future research, empirical data ought to be combined to carry out more comprehensive studies, so as to improve the depth of model research and make the conclusions more applicable.

ACKNOWLEDGMENTS

This work was supported in part by the National Natural Science Foundation of China (71972060).

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