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Research on Green Design Strategy of Electrical and Electronic Manufacturing Enterprises Based on the Perspective of Tripartite Evolutionary Game

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Abstract: Green design emphasizes the environmental attributes of the product life cycle, which can prevent environmental pollution at the source and reduce resource consumption. Based on the evolutionary game theory, this paper constructs a tripartite game model between “government-electrical and electronic manufacturing companies-consumers”, explores the influence of participants’ strategic choices and parameters on the evolutionary behavior of the three parties in different situations, and uses Matlab software to conduct numerical simulation analysis. Simulation analysis is the process of simulating real-world events and system behavior through computer models to assess, validate, and predict their performance and response. The research results show that the strategic choices of the three parties influence each other and government supervision and green consumption are conducive to incentivizing manufacturing companies to carry out green design. Consumer green preferences, environmental tax rates, corporate recycling revenue, and increases in consumer recycling revenue are all conducive to product design. Compared to environmental taxes, corporate subsidy policies have a greater impact on the behavior of the government, manufacturing companies, and consumers. Compared to consumer subsidies, corporate subsidy policies have a more significant effect on the behavior of governments and manufacturing companies, while for consumers, the opposite is true.

Keywords: green product design; evolutionary game; government policy; green consumption; consumer green preference



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1. Introduction

Since its reform and opening up, China’s industrial economy has developed rapidly and has become the main driver of GDP growth. However, the development mode at the expense of the environment has caused resource, environment, and ecological problems to become more and more serious, and instead has restricted the development of the economy. To solve this problem, China has proposed “green manufacturing” to transform the traditional development model and realize the green, low-carbon, and sustainable development of the manufacturing industry. The goal of green manufacturing is to adopt green design in the whole life cycle of product design, manufacturing, use, and end-of-life, and integrate waste recycling strategies to form a closed-loop system. This not only helps to reduce the environmental impact of the production process but also enables sustainable development through the recycling of resources [1]. Among them, the dismantling and recycling of products are considered, in detail, at the early stage of the design of electrical and electronic products so as to achieve resource conservation and recycling cost reduction at the end of the product life cycle. This design approach helps to optimize product structure and increase material recycling rates, thereby reducing environmental pollution and resource waste at the end of product life [2]. The green design stage is part of the design

stage of the product, taking into account environmental factors and pollution prevention measures so that the impact of the product on the environment is minimized, which is the key link of green product development. Ye and Zhang [3] showed that green design has a significant positive impact on both environmental and economic performance. However, due to the technical difficulties and risks in green product design and the uncertainty of existing environmental regulations, the enthusiasm of manufacturing enterprises to adopt green design is not high and the ability to produce green innovation is insufficient. Electrical and electronic products in industrial products have become deeply rooted in our daily lives, greatly improving our quality of life and convenience. However, with the acceleration in upgrading these products, the disposal of waste electrical and electronic products has become increasingly prominent, which has become a challenge that all parties must face together. To effectively manage and recycle these discarded electronic products, measures need to be taken at the source, which is the starting point of the tripartite game between businesses, governments, and consumers. As the executors of green design and production, electrical and electronic manufacturing enterprises need to realize that green design not only helps to reduce environmental pollution but also improves the market competitiveness of products. Enterprises should actively explore green design strategies and increase investment in innovation to meet the growing demand for green consumption. The role of the government is to formulate and enforce regulations and standards related to green design, strengthen the supervision mechanism in the early stages of green design implementation, and ensure that enterprises comply with relevant regulations and standards. As the market matures and consumers become more environmentally conscious, the regulatory mechanism can gradually transition to self-regulation, driven by the innovation of manufacturing enterprises and the ecological awareness of consumers to achieve more efficient and sustainable green development. In addition, as an important subject of market participation and as the market demand for green products grows, consumer choice has become more and more important. By educating consumers about the benefits of green products and guiding them to change their consumption patterns, we can effectively advocate for a societal shift towards eco-friendliness and resource conservation. This will not only raise consumer awareness of environmental protection but also inspire companies to adopt more environmentally friendly production methods through changes in market demand.

In short, this self-regulatory model, driven by corporate innovation and consumer ecological awareness, will achieve more efficient and sustainable green development. Encouraging manufacturing enterprises to carry out green design, increasing their investment in innovation in green product design, and leading consumers to establish the concept of green consumption, will play a vital role in solving the environmental problems of electrical and electronic products and promoting green development in China's manufacturing industry. Through the joint efforts and smart games of enterprises, governments, and consumers, we can look forward to a more sustainable and environmentally friendly future.

2. Literature Review

Some scholars have studied the impact of government subsidies and tax policies on green design. Sun and Yu [4] established a two-stage game model in which the government subsidizes green producers or consumers in the green supply chain, and found that both subsidy policies can promote the development of green products through numerical simulation. Guo and He [5] used game and optimization theory to study the impact of government subsidies on social welfare and the profits of supply chain members and found that the government's choice of subsidy policies depends on consumers' sensitivity to prices. Sharif and Mohsin [6] established a three-stage game model of "government-enterprise-consumer" to study the impact of government subsidy policies on green product design. Zhang and Lu [7] constructed a tripartite evolutionary game model of the government, automakers, and consumers in the new energy vehicle industry, showing that the unilateral evolution

strategy will be affected by the other participating strategies at the same time, and the evolution speed of car companies changes with government subsidies. Ma et al. [8] constructed a Stackelberg game model between retailers and (non-)green manufacturers, showing that government subsidies and taxes have an impact on both supply chain strategies, but the subsidy mechanism is more effective. Most existing studies are based on the green supply chain to study the impact of government subsidies and tax policies on the entire supply chain. Less studies consider the impact of green design on the tripartite evolution strategy in the tripartite evolutionary game of “government-electrical and electronic manufacturing enterprises-consumers”.

Other scholars have studied the impact of consumer behavior on green design. Feng et al. [9] show that consumer environmental awareness can improve corporate profits. Li et al. [10] constructed an evolutionary game model of manufacturing enterprises and consumers, and analyzed the impact of consumer acceptance on production and consumption strategies, showing that when consumers have a high acceptance of green products, enterprises and consumers tend to favor green production and green consumption. Sinayi and Rasti [11] constructed a two-level model composed of the supply chain and government and took consumer surplus as a social welfare indicator, indicating that the inclusion of part of consumer surplus in government utility functions has a greater impact on the profits of supply chain members and the greenness of products. Hong et al. [12] considered the impact of consumers’ reference behavior and environmental awareness on the design of green products in the secondary supply chain and found that consumers’ reference behavior and environmental awareness significantly influenced the design and pricing decisions of enterprises’ green products. However, the importance of green design in the electrical and electronic products industry is rising, but there is still a relative lack of research on how consumer preferences shape product design decisions. Specifically, when consumers show a higher preference for green products, they may be more inclined to pay a premium for electronic products that incorporate environmentally friendly features, which provides a direct financial incentive for companies to implement green design. At the same time, consumers’ green preferences may also drive companies to consider environmental factors at the early stage of product design to meet market demand and enhance the competitiveness of products in the market. Overall, although most existing studies have investigated the strategic choices of electrical and electronic manufacturing enterprises from the perspective of government policies, few studies have been conducted from the perspective of market demand. This paper aims to fill this gap and analyze the impact of consumers’ green preference on the greenness of green design of electrical and electronic products. At the same time, the dual impact of government policies and consumer demand on the strategy of electrical and electronic manufacturing enterprises is considered.

Also relevant to this article is the recycling of waste electrical and electronic products. To achieve environmental protection and resource conservation, the first step is to carry out green design for products and reduce environmental pollution at the beginning of the product life cycle, and the other is to recycle and reuse waste products [13] to save resources at the end of the product life cycle. Hu et al. [14] studied the government’s incentives for manufacturers to collect funds for waste electrical and electronic products and proposed mixed contracts and separation contracts. Li and Zheng [15] analyzed the statistical data on the treatment and recycling of waste gas, electrical, and electronic products in China from 2009 to 2019, found the existing problems, and proposed a combination of direct government supervision and indirect market supervision to improve the incentive system for ecological design and harmless disposal. Wang et al. [16] built a closed-loop supply chain consisting of suppliers (leaders) and manufacturers (followers) to solve the problem of waste of electrical and electronic equipment and encourage green product design. Most existing studies adopt end-of-line management for the recycling of waste electrical and electronic products, and rarely consider the dismantling and recycling of electrical and electronic products at the early stage of product design, so as to reduce recycling costs and save resources. Therefore, for manufacturing companies, it is necessary not only to

carry out green design, but also to recycle waste products in the product life cycle to form a closed loop.

From the literature reviews, it can be seen that the research on green development in China and abroad mainly focuses on green production, green technology innovation [17,18], and remanufacturing green innovation [19]. Most of the research related to green design is conducted from the micro-perspective of product or component process design improvement, and the impact of green design on manufacturing enterprises is rarely studied from the macro-perspective of the government and the market. Secondly, most of the existing literature is based on the green supply chain analysis framework, and the impact of green design on the tripartite evolution strategy of “government-electrical and electronic manufacturing enterprises-consumers” is rarely considered in the tripartite evolutionary game, and the green design and waste product recycling of manufacturing enterprises are rarely considered at the same time. This paper studies the impact of government and consumer strategic behaviors on the strategic behaviors of electrical and electronic manufacturing enterprises from the aspects of a government reward and punishment mechanism and consumers’ green consumption behaviors, constructs a green design evolution game model with the participation of “government-electrical and electronic manufacturing enterprises-consumers”, and uses Matlab R2020a to conduct numerical simulations to analyze the changes of system equilibrium strategies in different scenarios and the evolutionary impact of different parameter changes on tripartite behaviors. At the same time, in order to stay ahead of the fierce market competition, companies must make strategic choices based on market demand and also consider the impact of government policies on production, operations, and product design. Therefore, this study will expand the scope of research to focus not only on green design innovation and production efficiency within enterprises but also to delve into the changing trends of market demand and how government policies shape the decision-making process of enterprises. Through this comprehensive analysis, we aim to provide electronics manufacturing companies with a comprehensive view of decision-making that helps them to achieve environmental sustainability and social responsibility while pursuing economic benefits. Through this analysis, research conclusions are drawn and effective and feasible suggestions are put forward which further enrich the theory of green development and provide a reference for the construction of a green design system driven by the government and the market.

3. Basic Assumptions and Model Building

3.1. Model Assumptions and Parametric Design

The three subjects involved in the green design of enterprises include: the government, electrical and electronic manufacturing enterprises, and consumers. The government can choose regulatory and non-regulatory strategies, electrical and electronic manufacturing enterprises can choose green design and ordinary design strategies, and consumers can choose green consumption and traditional consumption strategies. Through learning and improvement, the three parties constantly adjust their strategies and seek the optimal strategy so that the system can achieve a stable equilibrium.

In the initial state, the tripartite participants “government”, “electrical and electronic manufacturing enterprises” and “consumers” under the capitalization operation mode are bounded rational “economic persons”, and the information held by the game subjects is incomplete and asymmetrical information. Through a certain strategy chosen by the other party, the other party can learn to change their own decisions to maximize their interests [20] and set a probability function, for which the following hypothesis H1 is proposed:

H1: *The government, electrical and electronic manufacturing enterprises, and consumers are all bounded rational. The probability that the government chooses to regulate is x , and the probability of not regulating is $1 - x$; the probability of electrical and electronic manufacturing enterprises choosing green design is y , and the probability of ordinary design is $1 - y$; the probability of*

consumers choosing green consumption is z ; and the probability of traditional consumption is $1 - z$, where $0 \leq x, y, z \leq 1$.

The level of product greenness can be reflected in the green design features of the product, such as energy efficiency labels, carbon labels, the content of hazardous substances, and the degree of recyclability of product parts [21].

H2: The greenness of the products produced by enterprises with green design is higher than the national minimum standard. To simplify the model, it is assumed that the greenness of the products produced by enterprises with ordinary design is 0, that is, $g > 0$. The greenness of the products designed by enterprises is constant, and the design cost of green design products has a quadratic relationship with the greenness of the products, that is, the total cost is ηg^2 [22], in which η is the cost coefficient of R&D investment for the green design of enterprises.

To capture the preferences and needs of each game agent so as to reflect its motivations and goals in the game, a more realistic game model is constructed, the agent behavior is predicted, and the strategy choice is analyzed [23]. Comprehensively considering the benefits and decision-making of all parties under the green product manufacturing system, the game subject selects the parameters according to behavior and firstly constructs the following demand parameters:

H3: The output of green design products of electrical and electronic manufacturing enterprises = the demand of consumers for green consumption = Q_1 , the output of ordinary design products of electrical and electronic manufacturing enterprises = the demand of traditional consumption of consumers = Q_2 , consumers' demand for products is rigid, that is, when consumers cannot buy the desired type of product, they must buy another type of product to meet their demand, but the utility loss caused by consumers not purchasing the desired product type is S .

Quantify the costs that a gambling agent needs to bear when adopting a specific strategy [24]. By setting the cost parameters, the decision-making process of the agent is more accurately simulated, the economic feasibility of different strategies is evaluated, and the strategy that maximizes the cost-effectiveness is found, and the following hypothesis, H4, is proposed:

H4: The unit cost of ordinary design products is C , and the cost of green design products is $C_H + C_W$, C_H refers to the cost of recycling products by green design enterprises, and C_W refers to the treatment costs of wastewater, waste gas, and toxic substances generated in the production process by green design enterprises. The unit price of ordinary design products is P , the unit price of green design products is $P + dg$, d is the greenness preference payment coefficient (that is, the fee that consumers are willing to pay for each additional unit of greenness), and dg is the additional price to be paid for a single green design product. When consumers carry out green consumption, the recycling of green design products by enterprises can reduce the cost of products and it can also be understood as the increase in unit income h of green design enterprises using recyclable parts when consumers carry out green consumption.

The return parameter sets the returns obtained by the players from different strategies, which helps to analyze how each agent chooses strategies based on the potential returns, and how to evaluate the impact of strategy changes on the overall returns [25]. The following hypothesis H5 is proposed:

H5: To encourage enterprises and consumers to choose green design and green consumption, the government's subsidy rates for enterprises and consumers are a and b , respectively. The government's return is R_1 when the enterprise chooses green design, and the government's income is R_2 when the enterprise chooses ordinary design. The fixed cost of government regulation is M , and the cost of environmental remediation in the later stage due to government non-regulation is L . The greenness

of the products produced by green design enterprises reaches the requirements so no environmental tax is levied on green design enterprises, and only environmental tax is levied on ordinary design enterprises with a tax rate of r .

To reflect the subjective satisfaction of each game agent with the return, utility parameters are set to help understand the risk appetite of each player, evaluate the subjective value of different outcomes, and predict their choices in the game [26].

H6: Under government regulation, all citizens receive environmental utility as U_e . When consumers choose traditional consumption, the expected unit utility of the product is U , and when consumers choose green consumption, the expected unit utility of the product is $U + kg$, k is the green preference coefficient of consumers, and kg is the additional utility obtained by consumers by purchasing green design products. Enterprises carry out green design, and the unit income obtained by green consumers for the return of recyclable products is w , assuming that all green design products purchased by consumers are recycled.

3.2. Construction of the Three-Way Game Model

Based on the assumptions and parameters of 3.1, the evolutionary game return matrix of the three participants is constructed, as shown in Table 1.

Table 1. Benefit matrix of the tripartite evolutionary game.

Policy Selection		Consumer	
		Green Consumption z	Traditional Consumption $(1 - z)$
Government regulation x	Enterprises choose green design y	$R_1 - M - aQ_1 - bQ_1,$ $(P + dg - C)Q_1 - C_H - C_w - \frac{1}{2}\eta g^2 + hQ_1 + aQ_1, U_e + (U + kg - P - dg + w)Q_1 + bQ_1$	$R_2 - M - aQ_1,$ $(P + dg - C)Q_1 - C_H - C_w - \frac{1}{2}\eta g^2 + hQ_1 + aQ_1, U_e + (U - P - dg)Q_1 - S$
	Business choice ordinary design $(1 - y)$	$R_1 - M + rQ_2 - bQ_2,$ $(P - C)Q_2 - rQ_2, U_e + (U - P)Q_2 + bQ_2 - S$	$R_1 - M + rQ_2,$ $(P - C)Q_2 - rQ_2, U_e + (U - P)Q_2$
The government does not regulate $(1 - x)$	Enterprises choose green design y	$R_2 - L,$ $(P + dg - C)Q_1 - C_H - C_w - \frac{1}{2}\eta g^2 + hQ_1, (U + kg - P - dg + w)Q_1$	$R_2 - L,$ $(P + dg - C)Q_1 - C_H - C_w - \frac{1}{2}\eta g^2, (U - P - dg)Q_1 - S$
	Business choice ordinary design $(1 - y)$	$R_1 - L,$ $(P - C)Q_2, (U - P)Q_2 - S$	$R_1 - L,$ $(P - C)Q_2, (U - P)Q_2$

4. Equilibrium Analysis of the Tripartite Evolutionary Game

This section will strengthen the role of evolutionary game theory in analyzing the complex interactions between government regulation, manufacturing firms, and consumer behavior through model analysis. Evolutionary game theory provides a powerful tool for analyzing the evolution and stability of strategies in multi-agent systems, especially for the dynamic and interactive process of green technology adoption. A tripartite evolutionary game model involving the government, manufacturing enterprises, and consumers was constructed to simulate the impact of different strategy choices on green design behavior. In this model, the government's regulatory strategy, the green design decisions of manufacturing companies, and consumers' green consumption preferences will be regarded as key variables in the evolutionary process. We will explore how these variables interact in differ-

ent contexts and how they work together to influence the promotion and implementation of green design.

4.1. Expected Reward Function

“Replication dynamics” and “evolutionary stability strategies” are the two core categories of evolutionary game theory. Among them, “replication dynamics” provides a dynamic description and analysis of the process of policy adjustment under bounded rationality [27]. The expected benefit functions of government, manufacturing companies, and consumer behavior strategies are constructed in the following sections.

4.1.1. Government Expected Revenue Function

Assuming that the expected returns of government regulation and non-regulation are U_{x_1} , U_{x_2} and the average expected returns of the government are $\bar{U}_x$. Table 1 shows that:

$$U_{x_1} = yz(R_1 - M - aQ_1 - bQ_1) + y(1 - z)(R_1 - M - aQ_1) + z(1 - y)(R_2 - M + rQ_2 - bQ_2) + (1 - y)(1 - z)(R_2 - M - rQ_2) \quad (1)$$

$$U_{x_2} = yz(R_1 - L) + y(1 - z)(R_1 - L) + z(1 - y)(R_2 - L) + (1 - y)(1 - z)(R_2 - L) \quad (2)$$

$$\bar{U}_x = xU_{x_1} + (1 - x)U_{x_2} \quad (3)$$

4.1.2. The Expected Return Function of the Manufacturing Enterprise

Assuming that the expected returns of electrical and electronic manufacturing enterprises choosing green design and general design are U_{y_1} , U_{y_2} and the average expected returns of enterprises are $\bar{U}_y$, Table 1 can be obtained:

$$U_{y_1} = xz[(P + dg - C)Q_1 - C_H - C_w - \frac{1}{2}\eta g^2 + hQ_1 + aQ_1] + x(1 - z)[(P + dg - C)Q_1 - C_H - C_w - \frac{1}{2}\eta g^2 + aQ_1] + z(1 - x)[(P + dg - C)Q_1 - C_H - C_w - \frac{1}{2}\eta g^2 + hQ_1] + (1 - x)(1 - z)[(P + dg - C)Q_1 - C_H - C_w - \frac{1}{2}\eta g^2] \quad (4)$$

$$U_{y_2} = xz(P - C - r)Q_2 + x(1 - z)(P - C - r)Q_2 + z(1 - x)(P - C)Q_2 + (1 - x)(1 - z)(P - C)Q_2 \quad (5)$$

$$\bar{U}_y = yU_{y_1} + (1 - y)U_{y_2} \quad (6)$$

4.1.3. The Function of Consumer Expected Returns

It is assumed that the expected returns of consumers choosing green consumption and traditional consumption are U_{z_1} , U_{z_2} and the average expected returns of consumers are $\bar{U}_z$, as can be obtained from Table 1:

$$U_{z_1} = xy[U_e + (U + kg - P - dg + w)Q_1 + \beta Q_1] + x(1 - y)[U_e + (U - P)Q_2 + bQ_1 - S] + y(1 - x)(U + kg - P - dg + w)Q_1 + (1 - x)(1 - y)[(U - P)Q_2 - S] \quad (7)$$

$$U_{z_2} = xy[U_e + (U - P - dg)Q_1 - S] + x(1 - y)[U_e + (U - P)Q_2] + y(1 - x)[(U - P - dg)Q_1 - S] + (1 - x)(1 - y)(U - P)Q_2 \quad (8)$$

$$\bar{U}_z = zU_{z_1} + (1 - z)U_{z_2} \quad (9)$$

4.2. Replicate Dynamic Analysis

After solving the expected return function under different strategy combinations, the replication dynamic equation is constructed and solved according to the evolutionary game theory under the combination of electrical and electronic manufacturing enterprises, the government, and consumers concerning previous scholars' research [28].

4.2.1. From Equations (1)–(3), the Dynamic Replication Equation for Government Policy Choice Can Be Determined

$$F(x) = \frac{dx}{dt} = x(U_{x_1} - \bar{U}_x) = x(1 - x)[-(aQ_1 + rQ_2)y - bQ_2z + (Q_2 - Q_1)byz - M + rQ_2 + L] \quad (10)$$

Deriving the replication dynamic equation of the government, we find:

$$F'(x) = (1 - 2x)[-(aQ_1 + rQ_2)y - bQ_2z + (Q_2 - Q_1)byz - M + rQ_2 + L]$$

4.2.2. From Equations (4)–(6), the Dynamic Replication Equation for the Strategic Choice of Electrical and Electronic Manufacturing Enterprises Can Be Determined

$$F(y) = \frac{dy}{dt} = y(U_{y_1} - \bar{U}_y) = y(1-y)[(aQ_1 + rQ_2)x + hQ_1z + (P + dg - C)Q_1 - C_H - C_w - \frac{1}{2}\eta g^2 - (P - C)Q_2] \quad (11)$$

Cause: $\pi_1 - \pi_2 = (P + dg - C)Q_1 - C_H - C_w - \frac{1}{2}\eta g^2 - (P - C)Q_2$.

Namely: $F(y) = \frac{dy}{dt} = y(U_{y_1} - \bar{U}_y) = y(1-y)[(aQ_1 + rQ_2)x + hQ_1z + \pi_1 - \pi_2]$.

Derivation of the replication dynamic equation of electrical and electronic manufacturing enterprises obtains:

$$F'(y) = (1-2y)[(aQ_1 + rQ_2)x + hQ_1z + (P + dg - C)Q_1 - C_H - C_w - \frac{1}{2}\eta g^2 - (P - C)Q_2]$$

4.2.3. The Dynamic Replication Equation for Consumer Strategy Choice Can Be Determined by Equations (7)–(9)

$$F(z) = \frac{dz}{dt} = z(U_{z_1} - \bar{U}_z) = z(1-z)[bQ_2x + (kgQ_1 + wQ_1 + 2S)y + (Q_1 - Q_2)bxy - S] \quad (12)$$

Deriving the replication dynamic equation of the consumer, we find:

$$F'(z) = (1-2z)[bQ_2x + (kgQ_1 + wQ_1 + 2S)y + (Q_1 - Q_2)bxy - S]$$

4.3. Stability Analysis

Equations (10)–(12) are the replication dynamic equations of the government, electrical and electronic manufacturing enterprises and consumers, respectively, reflecting the process of continuous learning and imitation of dynamic strategy selection among the three participants. In order to obtain the equilibrium point for the government, electrical and electronic manufacturing enterprises, and consumers to reach the stable state of the evolutionary game, the three replication dynamic equations are equal to 0, that is, $F(x) = 0$, $F(y) = 0$, and $F(z) = 0$, and 9 equilibrium points are obtained, which are $E_1 = (0,0,0)$, $E_2 = (0,0,1)$, $E_3 = (0,1,1)$, $E_4 = (0,1,0)$, $E_5 = (1,0,0)$, $E_6 = (1,0,1)$, $E_7 = (1,1,0)$, $E_8 = (1,1,1)$, $E_9 = (x^*, y^*, z^*)$, $E_9 = (x^*, y^*, z^*)$ are the internal equilibrium points, which are non-asymptotic steady states [29]. Therefore, only the asymptotic stability of the remaining 8 equilibrium points is analyzed.

According to Lyapunov's stability theory [30], the eigenvalues of the Jacobian matrix can be used to determine whether the above equilibrium points have asymptotic stability. Referring to the game theory research from Zhu Lilong et al. [31] and Okuguchi and Yamazaki [32], the Jacobian matrix of the dynamic game of the government, electrical and electronic manufacturing enterprises, and consumers [33] is as follows:

$$J = \begin{bmatrix} \frac{\partial F_x}{\partial x} & \frac{\partial F_x}{\partial y} & \frac{\partial F_x}{\partial z} \\ \frac{\partial F_y}{\partial x} & \frac{\partial F_y}{\partial y} & \frac{\partial F_y}{\partial z} \\ \frac{\partial F_z}{\partial x} & \frac{\partial F_z}{\partial y} & \frac{\partial F_z}{\partial z} \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{bmatrix}$$

Thereinto:

$$\begin{aligned} a_{11} &= (1-2x)[-(aQ_1 + rQ_2)y - bQ_2z + (Q_2 - Q_1)byz - M + rQ_2 + L] \\ a_{12} &= x(1-x)[-aQ_1 - rQ_2 + (Q_2 - Q_1)bz] \\ a_{13} &= x(1-x)[-bQ_2 + (Q_2 - Q_1)by] \\ a_{21} &= y(1-y)(aQ_1 + rQ_2) \\ a_{22} &= (1-2y)[(aQ_1 + rQ_2)x + hQ_1z + \pi_1 - \pi_2] \\ a_{23} &= y(1-y)hQ_1 \\ a_{31} &= z(1-z)[bQ_2 + (Q_1 - Q_2)by] \\ a_{32} &= z(1-z)[kgQ_1 + wQ_1 + 2S + (Q_1 - Q_2)bx] \\ a_{33} &= (1-2z)[bQ_2x + (kgQ_1 + wQ_1 + 2S)y + (Q_1 - Q_2)bxy - S] \end{aligned}$$

Using Lyapunov's first law: If the eigenvalues of matrix J are all negative, the equilibrium point is the evolutionary stability strategy (ESS). If the eigenvalues are all positive, the equilibrium point is the unstable point; If one or both of the eigenvalues are positive, the equilibrium point is the saddle point. Table 2 shows the eigenvalues of the equilibrium points of the system and their judgments.

Table 2. Equilibrium points and their eigenvalues of the system.

Equilibrium Point	Matrix Eigenvalues			Progressive Stability
	λ_1	λ_2	λ_3	
$E_1 (0,0,0)$	$-M + rQ_2 + L$	$\pi_1 - \pi_2$	$-S$	condition ①
$E_2 (0,0,1)$	$-bQ_2 - M + rQ_2 + L$	$hQ_1 + \pi_1 - \pi_2$	S	instability
$E_3 (0,1,1)$	$-aQ_1 - bQ_1 - M + L$	$-hQ_1 + \pi_2 - \pi_1$	$-kgQ_1 - wQ_1 - S$	condition ②
$E_4 (0,1,0)$	$-aQ_1 - M + L$	$\pi_2 - \pi_1$	$kgQ_1 + wQ_1 + S$	instability
$E_5 (1,0,0)$	$M - rQ_2 - L$	$\pi_1 - \pi_2$	$bQ_2 - S$	condition ③
$E_6 (1,0,1)$	$bQ_2 + M - rQ_2 - L$	$aQ_1 + rQ_2 + hQ_1 + \pi_1 - \pi_2$	$S - bQ_2$	condition ④
$E_7 (1,1,0)$	$aQ_1 + M - L$	$-aQ_1 - rQ_2 + \pi_2 - \pi_1$	$kgQ_1 + wQ_1 + bQ_1 + S$	instability
$E_8 (1,1,1)$	$aQ_1 + bQ_1 + M - L$	$-aQ_1 - rQ_2 - hQ_1 + \pi_2 - \pi_1$	$-kgQ_1 - wQ_1 - bQ_1 - S$	condition ⑤

Taking $E_1 (0,0,0)$ as an example, the eigenvalues of the Jacobian matrix are $\lambda_1 = -M + rQ_2 + L$, $\lambda_2 = \pi_1 - \pi_2$, $\lambda_3 = -S$, if λ_1 , λ_2 , and λ_3 meet the condition ①, that is $-M + rQ_2 + L < 0$, $\pi_1 - \pi_2 < 0$, $-S < 0$, then $E_1 (0,0,0)$ is ESS. Table 3 shows the stability conditions for other equilibrium points:

Table 3. Stability conditions of the system equilibrium point.

Equilibrium Point	Stability Conditions	Numbering
$E_1 (0,0,0)$	$-M + rQ_2 + L < 0$, $\pi_1 - \pi_2 < 0$, $-S < 0$	condition ①
$E_3 (0,1,1)$	$-aQ_1 - bQ_1 - M + L < 0$, $-hQ_1 + \pi_2 - \pi_1 < 0$, $-kgQ_1 - wQ_1 - S < 0$	condition ②
$E_5 (1,0,0)$	$M - rQ_2 - L < 0$, $\pi_1 - \pi_2 < 0$, $bQ_2 - S < 0$	condition ③
$E_6 (1,0,1)$	$bQ_2 + M - rQ_2 - L < 0$, $aQ_1 + rQ_2 + hQ_1 + \pi_1 - \pi_2 < 0$, $S - bQ_2 < 0$	condition ④
$E_8 (1,1,1)$	$aQ_1 + bQ_1 + M - L < 0$, $-aQ_1 - rQ_2 - hQ_1 + \pi_2 - \pi_1 < 0$, $-kgQ_1 - wQ_1 - bQ_1 - S < 0$	condition ⑤

5. Scenario Simulation Analysis

Through the above stability analysis, it can be seen that in the tripartite evolutionary game, the choice of the evolutionary game strategy of any participant will change with the probability change of the other two parties participating in the choice of the agent's strategy, and the evolutionary equilibrium has certain conditions. In order to analyze the dynamic evolution process of government, electrical and electronic manufacturing enterprises, and consumers more intuitively, this paper uses Matlab to simulate and analyze different scenarios to obtain reasonable scenarios, and analyze the impact of different parameter changes on the evolution process. Based on the existing research results and the actual background [34–36], this study considers the rationality of the values of each parameter, proposes the basic values of each parameter, and assumes that the parameter values of the five scenarios are shown in Table 4.

Table 4. Parameter values.

Scenario	P	d	g	C	C_H	C_W	Q_1	Q_2	η	h	M	r	a	b	k	S	w	L
One	1	0.2	1.2	0.6	3	8	10	20	1	0.2	10	0.2	0.3	0.13	0.5	2	0.1	2
Two	1	0.2	1.2	0.6	3	8	20	10	1	0.2	3	0.2	0.3	0.13	0.5	2	0.1	2
Three	1	0.2	1.2	0.6	5	10	10	20	1	0.2	3	0.2	0.3	0.13	0.5	6	0.1	4
Four	1	0.2	1.2	0.6	3	8	10	20	1	0.2	3	0.2	0.3	0.13	0.5	2	0.1	4
Five	1	0.2	1.2	0.6	3	8	20	10	1	0.2	1	0.2	0.3	0.13	0.5	2	0.1	12

5.1. Evolutionary Game Outcomes in Different Contexts

5.1.1. Scenario 1

Under the premise of satisfying condition ①, when the government chooses not to supervise, the manufacturing enterprise chooses ordinary design, and the consumer chooses traditional consumption, the equilibrium point $E_1 (0,0,0)$ is reached, which is the evolutionary stability strategy ESS, as shown in Figure 1. From condition ①, it can be seen that when the regulatory cost is $-M + rQ_2 + L < 0$, $\pi_1 - \pi_2 < 0$, $-S < 0$, the government is greater than the sum of the environmental tax levied on ordinary design enterprises and the governance cost when the government does not supervise, the government's behavior will eventually tend towards a non-regulatory strategy. As far as manufacturing enterprises are concerned, there is no subsidy preference from the government, the profit of producing green design products is lower than the profit of producing ordinary design products, and the behavior of manufacturing enterprises will eventually tend towards ordinary design strategies. The lack of government incentives and the lack of green design by manufacturing companies have led to consumer behavior eventually shifting towards traditional consumption strategies. This scenario is not in line with the country's concept of green development, and this equilibrium is not ideal.

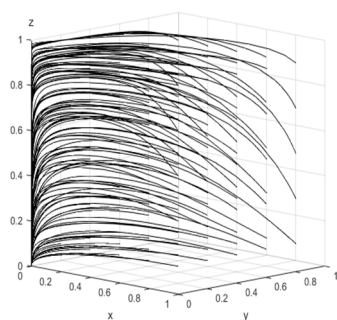


Figure 1. The results of the tripartite evolutionary game in scenario 1.

5.1.2. Scenario 2

Under the premise of satisfying condition ②, when the government chooses not to supervise and the manufacturing enterprise chooses green design and consumers choose green consumption, the equilibrium point $E_3 (0,1,1)$ is reached, which is the evolutionary stability strategy ESS, as shown in Figure 2. From condition ②, it can be seen that when the sum of the government is $-aQ_1 - bQ_1 - M + L < 0$, $-hQ_1 + \pi_2 - \pi_1 < 0$, $-kgQ_1 - wQ_1 - S < 0$, its regulatory costs and the government's subsidies for green design enterprises and green consumers is greater than the governance costs when the government does not regulate, the government's behavior will eventually tend towards a non-regulatory strategy. As far as manufacturing enterprises are concerned, when the sum of the profit obtained from the production of green design products and the income obtained from recycling recyclable products is greater than the profit from the production of ordinary design products, the behavior of manufacturing enterprises will eventually tend towards green design strategy. When the sum of the consumer's return to recyclable products, the additional utility obtained by green consumption and the utility lost due to the failure to purchase the desired product type is greater than 0, the consumer's behavior will eventually tend towards a green consumption strategy. This scenario occurs in the mature stage of implementing green design, which is the optimal equilibrium state, but it requires early government intervention to help consumers establish the concept of green consumption, and at the same time supervise manufacturing enterprises.

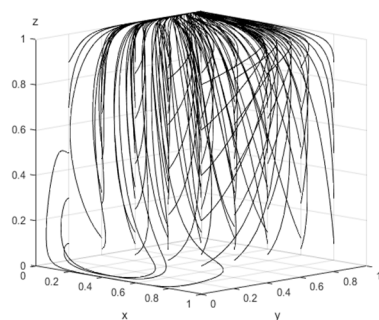


Figure 2. The results of the tripartite evolutionary game in scenario 2.

5.1.3. Scenario 3

Under the premise of satisfying condition ③, when the government chooses supervision, manufacturing enterprises choose ordinary design and consumers choose traditional consumption, the equilibrium point $E_5 (1,0,0)$ is reached, and the evolutionary stability strategy ESS is achieved, as shown in Figure 3. From condition ③, it can be seen that when $M - rQ_2 - L < 0$, $\pi_1 - \pi_2 < 0$, $bQ_2 - S < 0$, the sum of the environmental tax levied by the government on manufacturing enterprises that choose ordinary design and the governance cost to be paid when they do not regulate are greater than the government's regulatory cost, the government's behavior will eventually tend to be a regulatory strategy. For manufacturing enterprises, when the profit of producing green design products is lower than the profit of producing ordinary design products, the behavior of manufacturing enterprises will eventually tend towards ordinary design strategies. For consumers, when the utility of the green consumption subsidy is obtained by the consumer from the government, minus the loss due to the failure to purchase, the desired product type is less than zero, the consumer's behavior will eventually tend towards a traditional consumption strategy. In this scenario, the government supervises, manufacturing enterprises carry out ordinary design, and consumers carry out traditional consumption, and only the government takes the lead to adopt a positive strategy. The manufacturing enterprises and consumers do not respond accordingly, and society cannot form a green consumption atmosphere, which is not ideal.

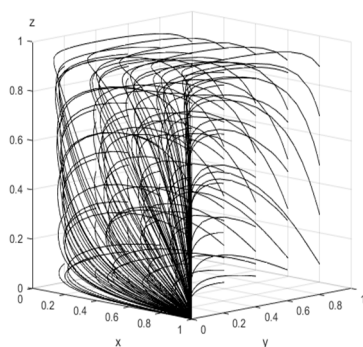


Figure 3. The results of the tripartite evolutionary game in scenario 3.

5.1.4. Scenario 4

Under the premise of satisfying condition ④, when the government chooses supervision, manufacturing enterprises choose ordinary design, and consumers choose green consumption, the equilibrium point $E_6 (1,0,1)$ is reached, and the evolutionary stability strategy ESS is reached, as shown in Figure 4. From condition ④, $bQ_2 + M - rQ_2 - L < 0$, $aQ_1 + rQ_2 + hQ_1 + \pi_1 - \pi_2 < 0$, $S - bQ_2 < 0$, it can be seen that when the sum of the environmental tax levied by the government on manufacturing enterprises that choose ordinary design and the governance cost to be paid when they do not regulate are greater than the sum of the consumer subsidies for green consumption and the government's regulatory cost, the government's behavior will eventually tend towards a non-regulatory

strategy. For manufacturing enterprises, when the sum of the income is obtained from the government's green design subsidies and the recycling of recyclable products and the profit from the production of green design products is less than the profit from the production of ordinary design products, minus the income obtained by the environmental tax imposed by the government on ordinary design enterprises, the behavior of manufacturing enterprises will eventually tend towards the ordinary design strategy. For consumers, when the green consumption subsidies they receive from the government are greater than the utility lost due to the type of product they do not purchase, their behavior will eventually tend towards traditional consumption strategies.

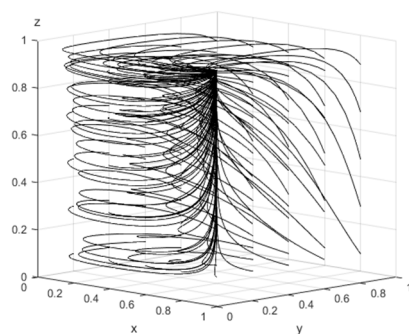


Figure 4. The results of the tripartite evolutionary game in scenario 4.

5.1.5. Scenario 5

Under the premise of satisfying condition ⑤, when the government chooses supervision, manufacturing enterprises choose green design, and consumers choose green consumption, the equilibrium point $E_8 (1,1,1)$ is reached, and the evolutionary stability strategy ESS is reached, as shown in Figure 5. From condition ⑤, it can be seen that when $aQ_1 + bQ_1 + M - L < 0$, $-aQ_1 - rQ_2 - hQ_1 + \pi_1 - \pi_2 < 0$, $-kgQ_1 - wQ_1 - bQ_1 - S < 0$, governance cost when the government does not regulate is greater than the sum of the government's subsidies for green design enterprises and green consumers and the cost of government supervision, the government's behavior will eventually tend towards a regulatory strategy. For manufacturing enterprises, when the sum of the benefits obtained from the government's green design subsidies and the recycling of recyclable products and the profits from the production of green design products is greater than the profits from the production of ordinary design products, minus the environmental taxes levied by the government on ordinary design enterprises, the behavior of manufacturing enterprises will eventually tend towards green design strategies. For consumers, when the sum of the green consumption subsidies obtained by consumers from the government, the benefits obtained from the return of recyclable products, the additional utility gained by green consumption, and the utility lost due to the type of product they did not purchase is greater than 0, the consumer's behavior will eventually tend towards green consumption strategy. Relative to the equilibrium point $E_3 (0,1,1)$, this scenario occurs in the initial stage of green design, and this equilibrium is reasonable, which is analyzed in detail below.

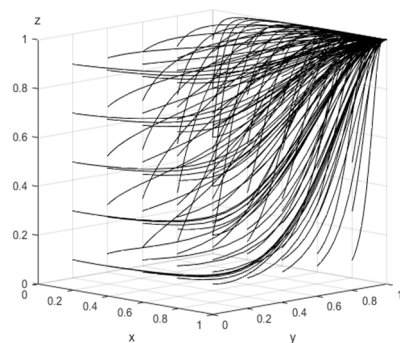


Figure 5. The results of the tripartite evolutionary game in scenario 5.

5.2. The Influence of Different Parameters on the Evolution Behavior of the Tripartite

5.2.1. Effect of Greenness g on Tripartite Evolutionary Behavior

Product greenness (g) reflects how environmentally friendly a product is during its life cycle. In the model, we assume that products with a green design have a greenness higher than the national minimum standard, while products with a normal design have a greenness of 0. With the increase in product greenness, consumers' preference and demand for green design products increases, which prompts manufacturing companies to be more inclined to choose green design strategies to meet market demand. Through green design, companies can provide products with higher environmental performance, thereby attracting more environmentally conscious consumers and increasing their market share and competitiveness. At the same time, the government has further promoted the transformation of enterprises and consumers towards green design and green consumption through regulation and incentives (such as subsidy policies), forming a positive cycle. Therefore, with the improvement in product greenness, the evolution strategy of the three parties tends towards (1,1,1), that is, (regulation, green design, green consumption).

Figure 6 illustrates the impact of green design product greenness on the tripartite evolution strategy. The threshold of product greenness is [9,10], and when the greenness of green design products is lower than the critical value, the evolution strategy of the government, manufacturing enterprises and consumers is (1,1,1), i.e., (regulation, green design, green consumption). When the greenness of green design products is higher than the critical value, the evolution strategy of the government, manufacturing enterprises and consumers is (1,0,0), i.e., (regulation, general design, traditional consumption). When the product is too green, the research and development cost of the company's green design is too high, which makes the company's profits decline, and at the same time, as the product greenness increases, the price of the product will increase at any time, and the consumer's expectation of the utility of the green design product decreases, and consumers turn to choose traditional consumption to buy ordinary design products.

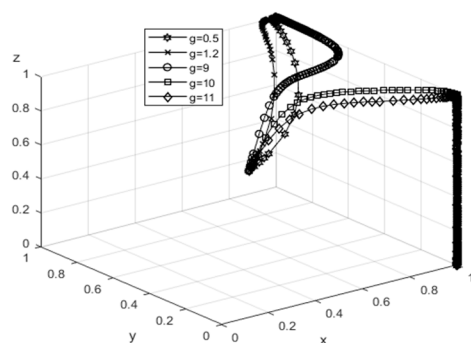


Figure 6. Evolution trend of tripartite game under different greenness.

5.2.2. The Impact of Consumers' Green Preference on the Evolutionary Behavior of the Three Parties

Numerical simulation analysis shows that consumers' green preferences will promote the evolution of the behavior of the three parties to the stable point (1,1,1). With the increase in consumers' green preference, the rate of convergence of consumer behavior to green consumption accelerates and the rate of convergence of government behavior to regulation decreases, which is mainly because when consumers' green preference grows higher and higher, consumers' awareness of green environmental protection becomes stronger and stronger, and manufacturing enterprises can be driven from the market side to evolve to green design strategies. It is also found that with the increase in consumers' green preference, the rate of convergence of manufacturing enterprises' behavior to green design increases, indicating that, in response to consumer demand, manufacturing enterprises strengthen their ability to design green products, improve their competitiveness, and occupy the green consumer market.

5.2.3. The Impact of Environmental Taxation on the Evolutionary Behavior of the Three Parties

Numerical simulation analysis shows that environmental taxes will promote the evolution of tripartite evolutionary behavior to a stable point (1,1,1) regardless of the size of the environmental tax. With the increase in the environmental tax rate, the rate of convergence of government behavior to a regulatory strategy accelerates, the rate of convergence of manufacturing enterprise behavior to green design strategy accelerates, and the rate of convergence of consumer behavior to green consumption strategy also accelerates. The higher the environmental tax rate levied by the government on ordinary design manufacturing enterprises, the more taxes the enterprises need to pay, which in turn reduces the profits of ordinary design products from these enterprises, and makes enterprises choose green design strategies. Enterprises increase the research and development and production of green design products and, at the same time, because the utility of green design products to consumers is higher than that of ordinary products, consumers will choose to buy green design products in order to obtain higher utility. Therefore, the environmental tax policy is conducive to enterprises improving their green innovation capabilities, choosing green design strategies, and promoting consumers' green consumption behavior from the supply side.

5.2.4. The Impact of Government Subsidies on the Evolutionary Behavior of the Three Parties

Enterprise subsidy (a) is an economic incentive provided by the government to incentivize enterprises to carry out green design. In the model, the amount of the subsidy influences the company's decision-making. Through simulation analysis, we can determine the threshold of a subsidy, and when the subsidy is below this value, the company may not choose green design because the subsidy is not enough to offset the increase in the cost of green design. When the subsidy is higher than this value, companies are more likely to choose green design.

Figure 7 illustrates the impact of government subsidies on corporate evolutionary strategies. The threshold of subsidies for enterprises is $[0.4, 0.5]$, and when the subsidies for enterprises are lower than the threshold, the evolution strategy of the government, manufacturing enterprises, and consumers is (1,1,1), that is, (regulation, green design, green consumption). When subsidies for enterprises are higher than the threshold, the evolution strategy of the government, manufacturing enterprises, and consumers is (0,1,1), i.e., (no regulation, green design, green consumption).

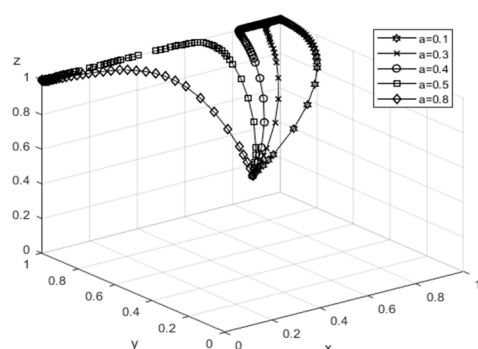


Figure 7. Evolution trend of tripartite game under different enterprise subsidies.

Next, the impact of environmental tax and enterprise subsidy policy on the evolution of the three parties is compared, and the analysis in Figure 8a–c shows that compared to environmental tax, government subsidies for enterprises have a greater impact on the behavior of governments, manufacturing enterprises, and consumers.

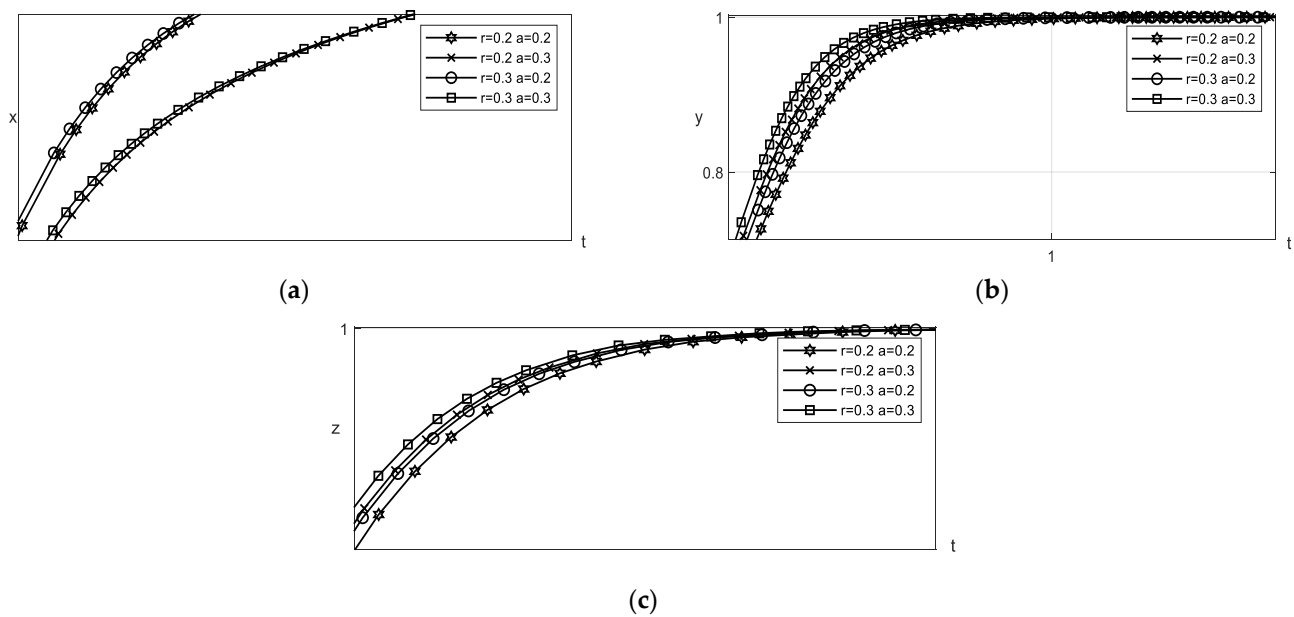


Figure 8. (a) Partial diagram of the evolutionary game of the government under different environmental taxes and corporate subsidies. (b) Partial diagram of the evolutionary game of manufacturing enterprises under different environmental taxes and corporate subsidies. (c) Partial diagram of the evolutionary game of consumers under different environmental taxes and corporate subsidies.

5.2.5. The Impact of Government Subsidies for Consumers on the Evolutionary Behavior of the Three Parties

Consumer subsidy (b) is an economic incentive provided by the government to encourage consumers to purchase green products. The amount of the subsidy will affect the consumer's purchasing decision. Through simulation analysis, we can determine a cut-off value for a subsidy, below which consumer purchasing behavior may not be significantly inclined toward green products. When subsidies are higher than this value, consumers are more likely to choose green consumption.

Figure 9 illustrates the impact of government subsidies on consumer subsidies on the tripartite evolutionary strategy. The threshold of consumer subsidies ranged from [0.2, 0.3], and when the consumer subsidies were lower than the threshold, the evolution strategies of the government, manufacturing enterprises and consumers were (1,1,1), i.e., (regulation, green design, green consumption). When the subsidy for consumers is higher than the threshold, the evolution strategy of the government, manufacturing enterprises, and consumers is (0,1,1), i.e., (no regulation, green design, green consumption).

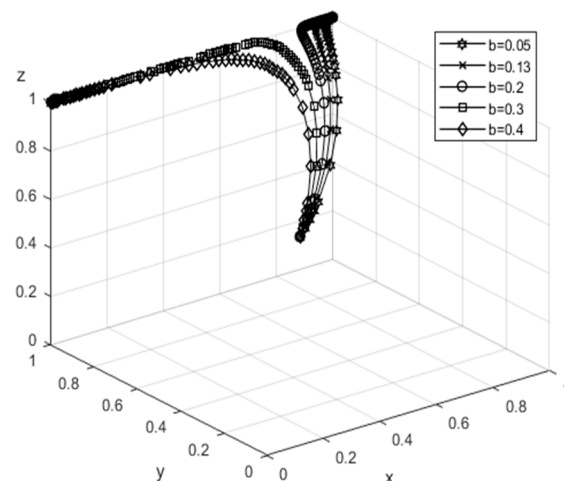


Figure 9. Evolution trend of tripartite game under different consumer subsidies.

Next, the impact of enterprise subsidies and consumer subsidies on the evolution of the three parties is compared, and the analysis in Figure 10a,b shows that compared to consumer subsidies, corporate subsidies have a greater impact on the behavior of governments and manufacturing enterprises. According to the analysis in Figure 10c, consumer subsidies have a greater impact on consumer behavior than corporate subsidies.

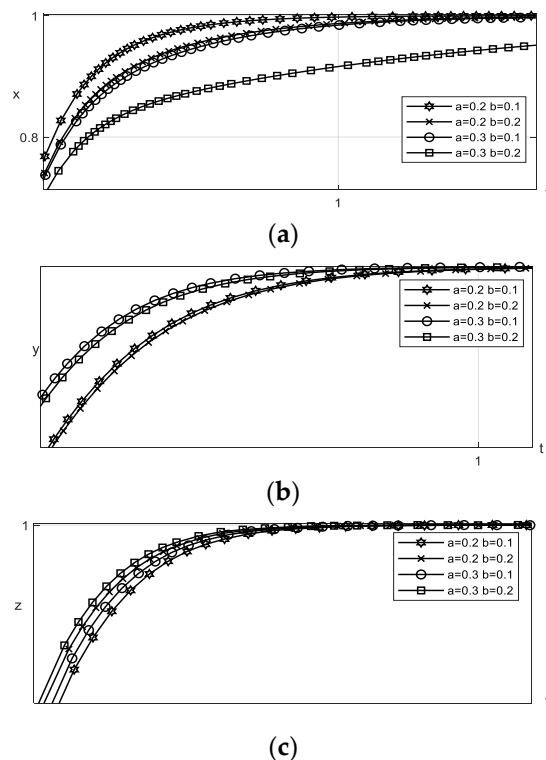


Figure 10. (a) Partial diagram of the evolutionary game of government under different enterprise subsidies and consumer subsidies. (b) Partial diagram of the evolutionary game of manufacturing enterprises under different enterprise subsidies and consumer subsidies. (c) Partial diagram of the evolutionary game of consumers under different enterprise subsidies and consumer subsidies.

5.2.6. The Impact of Corporate Recovery Revenue on the Evolutionary Behavior of the Three Parties

Numerical simulation analysis shows that tripartite evolution behavior will evolve to the stable point (1,1,1) regardless of the size of the company's recovery income. With the increase in corporate recycling revenue, the convergence rate of government behavior to regulatory strategy decreases, the convergence rate of manufacturing enterprise behavior to green design strategy accelerates, and the convergence rate of consumer behavior to green consumption strategy accelerates. Due to the detachability and recyclability of green design products, manufacturing enterprises can recycle reusable parts, which can reduce the procurement cost and production cost of enterprises and greatly increase corporate profits.

5.2.7. The Impact of Consumer Recovery Revenue on the Evolutionary Behavior of the Three Parties

Numerical simulation analysis shows that the tripartite evolution behavior will evolve to a stable point (1,1,1) regardless of the size of consumer recovery income. With the increase in consumer recycling benefits, the rate of convergence of government behavior to regulatory strategy decreases, the rate of convergence of manufacturing enterprise behavior to green design strategy accelerates, and the convergence rate of consumer behavior to green consumption strategy accelerates. To improve the green demand of the market, manufacturing enterprises actively carry out green innovation and improve green design capabilities, which will also lead to a decline in the rate of government supervision.

6. Discussion

Based on the evolutionary game theory, this study constructs and analyzes a tripartite evolutionary game model between the government, electrical and electronic manufacturing enterprises, and consumers, aiming to explore the strategic choices of each subject in different scenarios and their impact on green design behavior. Using numerical simulation analysis by Matlab software, we discuss the following:

1. Interaction of strategy selection: There is a significant interaction between the government's regulatory policies, enterprises' green design decisions, and consumers' green consumption preferences. The active supervision from the government and the green consumption tendency of consumers can effectively promote the implementation of green design by manufacturing enterprises, and the green design of enterprises can enhance consumers' willingness to buy green.
2. Identification of ideal scenarios: This study identified two ideal scenarios, namely the equilibrium between government regulation and market self-regulation. In the initial stages of green design, government regulation is necessary to ensure that companies adopt green design strategies; In the mature stage, market mechanisms can self-regulate, and the government can intervene less.
3. Comparison of policy instruments: This study finds that the corporate subsidy policy has a greater impact on the behavior of the government, manufacturing enterprises, and consumers than the environmental tax policy. At the same time, the impact of consumer subsidy policies on consumer behavior is more significant. This suggests that the combination of different policy tools should be considered when formulating policies related to green design.
4. The promotion of recycling income: The increase in corporate recycling income and consumer recycling income is conducive to promoting the evolution of the three parties to green design strategies. This underscores the importance of establishing an effective product recycling mechanism in promoting green design.
5. Governments should provide incentives for 'green' and 'non-green' companies to adopt positive environmental practices in the early stages of green design adoption in a combination of subsidies and tax policies. This policy mix can effectively reduce the initial cost of implementing green design while improving long-term environmental performance.
6. The Ministry of Industry and Information Technology (MIIT) should expand the scope of the application of green design standards to include more product categories and enrich the dimensions of such standards and contain a wider range of electrical and electronic products. This includes, but is not limited to, consumer electronics, home appliances, communication equipment, and industrial electronics. The focus should not only be on the energy efficiency and material selection of the product but also on the durability, repairability, upgradability, and eventual recycling of the product.

7. Conclusions

Based on the evolutionary game theory, a tripartite evolutionary game model of the government, electrical and electronic manufacturing enterprises, and consumers is constructed to explore the strategic choices of each subject in different scenarios and the influence of the parameters involved in the ideal scenario on the evolutionary behavior of the three parties. Through numerical simulation using Matlab, the following conclusions are drawn:

1. The strategy choice between the government, electrical and electronic manufacturing enterprises, and consumers affects each other, and the optimal strategy will be selected under different conditions. In this paper, five possible scenarios are analyzed, and the equilibrium points E_3 (0,1,1) and E_8 (1,1,1) are the most reasonable scenarios. The equilibrium point in the initial stage of implementing green design is E_8 (1,1,1), and the government needs to supervise at this stage. The equilibrium point for the mature stage of green design implementation is E_3 (0,1,1) when the government does not need to supervise.

2. Government supervision and consumer green consumption are conducive to motivating manufacturing enterprises to choose green design. In scenario 5, the analysis shows that the cut-off range of product greenness is [9,10], the cut-off range of corporate subsidies is [0.4, 0.5], and the cut-off range of consumer subsidies is [0.2, 0.3]. The simulation found that the increase in consumers' green preference, environmental tax rate, corporate recycling income, and consumer recycling income were beneficial to green product design.
3. The results show that, compared to environmental tax, corporate subsidy policy has a greater impact on the behavior of the government, manufacturing enterprises, and consumers. Compared to consumer subsidies, corporate subsidy policies have a greater impact on the behavior of governments and manufacturing enterprises, and appropriate corporate subsidies can reduce the economic pressure on enterprises and promote the development of green design, while consumers are the opposite.

The above conclusions can provide a reference for the government to formulate reward and punishment policies and the innovation strategy of green design of enterprise products. Of course, there are certain limitations in this study, first of all, only the design, production, and recycling links are considered in the model for the whole life cycle of the product, and the sales and product processing links are not involved, which is also an important direction of future research. Secondly, due to the limitations of data acquisition, the parameter assignment lacks the support of some actual data. Future research can also expand the implementation and impact of green design from the perspective of the supply chain of suppliers, manufacturers, and retailers.

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