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Analyzing Technological Innovation Diffusion: An Evolutionary Game Approach from a Dual Supply-Demand Perspective

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Abstract: This study investigates the diffusion of technological innovation within a market-driven framework by employing evolutionary game analysis. We develop a model from a dual supply-demand perspective, integrating enterprise production and consumer purchasing behavior. The model incorporates market variables such as revenue, costs, and consumer characteristics, utilizing MATLAB software for simulation to assess the impact of these factors on the strategic decisions of both enterprises and consumers. The findings reveal that the perceived value of innovative products and consumer acceptance facilitate the diffusion of technological innovation, whereas the perceived value and perceived loss associated with traditional products hinder this diffusion. Furthermore, the propensity of enterprises to adopt technological innovations is strongly linked to consumer demand for innovative products, with enterprises showing a greater inclination to embrace new technologies in response to heightened innovation demand.

Keywords: technological innovation diffusion, market-driven, evolutionary game, dual supply-demand

INTRODUCTION

The core of technological innovation lies in introducing inventions or other scientific and technological achievements into the production or value creation process, thereby generating products or services that meet new market demands. Through market value exchange, these inventions are subsequently converted into tangible wealth or new productive forces. Enterprises, as the main agents of innovation, are a necessary result of economic development. Consumers, as one of the primary forces in market value exchange (Chan et al., 2012; Zhu and He, 2017), can drive enterprises to determine research and development directions from the demand side, thereby fundamentally promoting technological innovation (Yu and Geng, 2024). Accordingly, this paper focuses on the diffusion of technological innovation from a dual perspective of the supply and demand relationship between enterprise production and consumer purchasing.

A common approach to studying the diffusion of technological innovation is to start from a macro perspective, using macro diffusion models, such as the Bass model (Bass, 1994; Bass, 2004) and its extended versions, to analyze and predict the extent, speed, and pattern of technology diffusion. Subsequently, many scholars have improved and refined the Bass model. For example, Xia and Deng (2019) analyzed the optimal level of government influence on the diffusion of industry-specific technologies based on a transformed Bass model, which captures the impact of government intervention on the diffusion speed and timeline of industry-specific technologies. Chen et al. (2010) pointed out the limitations of using the Bass model to study technological innovation diffusion in industrial clusters. In response, they expanded and established a modified Bass model for technological innovation diffusion in industrial clusters, conducting simulations, analyses, and comparison. Liu et al. (2023) combined the characteristics of live-streaming sales by officials to construct a BASS-SEIR dual-layer diffusion model, investigating the diffusion patterns and influencing factors of agricultural products. However, macro models typically study the diffusion of technological innovation from an overall perspective, overlooking the potential effects of individual adopters' characteristics on the diffusion process.

In recent years, an increasing number of scholars have applied game theory to study the mechanism of technological innovation diffusion from a micro perspective. Some scholars have approached the issue from the perspective of a free market, investigating the evolutionary behavior of technology innovation diffusion between enterprises under pure market mechanisms. For example, Xiao and Wang (2017) constructed a non-cooperative evolutionary game model on the diffusion of low-carbon environmentally friendly technological innovations between enterprises, proposing that technology complementarity parameters have a positive effect on the diffusion of technological innovation. Sun et al. (2019) approached the study from the two different relationships of competition and cooperation between enterprises, respectively constructing game models for technology adoption decisions to study the factors influencing technology diffusion under these different relationships. Based on the supply chain viewpoint, Yang and Zhou (2022) developed a game model on the dissemination of innovation between manufacturers and suppliers, modeling and examining the effects of elements like patent fees and “free-rider” benefits on the innovation diffusion evolution trajectory.

In terms of research methods, previous scholars have mostly employed system dynamics (Xu and Zhu, 2016), empirical analysis (Hu et al., 2023), and deterministic evolutionary models to explore the impact of various variables on technological innovation from a static equilibrium perspective. Some models incorporate dynamic evolution components but fail to accurately describe the interaction of interests between innovation agents and demand agents in the diffusion of technological innovation. In contrast, the stochastic evolutionary model used in this paper emphasizes a dynamic equilibrium, which can accurately depict the changes in impact between different variable values.

CONSTRUCTION OF EVOLUTIONARY GAME MODEL

Model Assumptions

Technological innovation diffusion is a selection process that encompasses both the decision to embrace innovative technology and the choice about its implementation. Simultaneously, it involves consumers' selection of enterprises, namely determining which types of items are generated by these entities. The participatory selection processes facilitate the broad dissemination of technological innovation successes in the market. Technological innovation disseminates incrementally. Consequently, when employing evolutionary game theory to elucidate stakeholder interactions in the diffusion process, it is imperative to simultaneously account for the dynamic fluctuations on both the supply and demand sides. Therefore, this paper selects enterprises and consumers as the primary entities of the game to investigate the extent of strategic influence and the factors that impact it.

- **Hypothesis 1:** Two main players in the process of technological innovation diffusion are businesses and consumers. Thus, these two types of subjects are selected as participants in the game. Both parties in the game are seen as "bounded rational economic entities", functioning under conditions of insufficient knowledge, computational limitations, and time constraints. They will implement techniques to optimize their personal interests in decision-making. The enterprise strategy set comprises {Adopt technological innovation, maintain tradition}, while the consumer strategy set consists of {Purchase innovative products, purchase traditional products}.
- **Hypothesis 2:** The probability of an enterprise choosing the strategy of "adopt technological innovation" is $x(0 \leq x \leq 1)$, the probability of choosing the strategy of "maintain tradition" is $1-x(0 \leq x \leq 1)$. If the probability of consumers choosing the strategy of " purchase innovative products" is $y(0 \leq y \leq 1)$, the probability of consumers choosing the strategy of " purchase traditional products" is $1-y(0 \leq y \leq 1)$.
- **Hypothesis 3:** The total market demand of the product is *Q*, the unit price of the innovative product is P_i, and the unit price of the traditional product is P_t. Innovative products typically exhibit enhancements in performance, aesthetics, and efficiency, resulting in a price that is frequently superior to that of traditional products ($P_i > P_t$). The unit cost of the innovative product is denoted as C_i, while the unit cost of the traditional product is C_t, with the condition that $C_i > C_t$. The product's price typically exceeds its cost, thereby fulfilling the conditions $P_i > C_i$ and $P_t > C_t$. Furthermore, only enterprises that embrace technological innovation are capable of producing innovative products; otherwise, they are limited to traditional products.
- **Hypothesis 4:** Consumers are expected to obtain a value of V_i by purchasing innovative products, while they are expected to obtain a value of V_t by purchasing traditional products, and $V_i > V_t$. In this paper, consumers are divided into two types: innovative and traditional. Innovative consumers have high expectations for product improvement, strong sensitivity to technological innovation, and are eager to try new things. Therefore, the strategy of "purchasing innovative products" is usually adopted. Traditional consumers attach importance to past consumption experience and do not easily try new products. Thus, they generally adopt the strategy of "purchasing traditional products". When there is no product on the market that meets the consumer's psychological expectations, the consumers have an acceptance $\lambda(0 < \lambda < 1)$ of products that do not meet their psychological expectations. However, consumers who change their choice incur a perceived loss, denoted *F*, for not buying the desired product.
- **Hypothesis 5:** The estimated cost input for an enterprise to adopt a technological innovation is *I*, which includes not only the input paid for the purchase of innovative technology. It also includes the cost of designing, debugging and testing before the enterprise formally applies the innovative technology to the production of products.

Based on the above assumptions, the symbols and meanings of the relevant parameters of the evolutionary game model are shown in Table 1.

Table 1: Symbols and meanings of parameters

Parameter	Meaning	Parameter	Meaning
Q	Product market demand	I	Estimated cost input for enterprises to adopt technological innovation
P_i	Innovative product prices	λ	Consumer acceptance
P_t	Traditional product prices	F	Consumer perceived loss
V_i	Consumers' Perceived Value of Innovative Products	C_i	Cost of innovative products
V_t	Consumers' Perceived Value of Traditional Products	C_t	Cost of traditional products

Model Construction

The strategic decisions of enterprises {adopting innovation, maintaining tradition} and consumers {purchasing innovative products, purchasing traditional products} reveal four combinations of two-party game strategies in a market-dominant context. Consequently, a game payoff matrix between enterprises and consumers is formulated, as shown in Table 2.

Table 2: Game payoff matrix of enterprise and consumer

Enterprise	Consumer	
	Purchasing innovative products $(\mathbf{y})$	**Purchasing traditional products** $(\mathbf{1-y})$
Adopting innovation (x)	$(P_i - C_i)Q - I$ QV_i	$\lambda(P_i - C_i)Q - I$ $\lambda Q(V_i - F)$
Maintaining tradition $(1-x)$	$\lambda(P_t - C_t)Q$ $\lambda(V_t - F)Q$	$(P_t - C_t)Q$ QV_t

When a firm chooses a strategy of adopting a technological innovation and consumers choose a strategy of purchasing the innovative product, the benefit $(P_i - C_i)Q$ of adopting the technological innovation is the operating profit earned from the sale of the innovative product, and the cost *I* is the projected cost of the input of adopting the technological innovation. The consumer's benefit from acquiring a unit of the innovative product is the perceived value of the product in its initial state (V_i), while the total gain is the product of the benefit derived from purchasing a unit and the sales volume, $Q(V_i + V)$. Likewise, the values of the game outcomes from the alternative strategy combinations can be derived.

Analysis of Replicator Dynamic Equation

According to the model assumptions and the payoff matrix, the benefit of adopting technological innovation is E_{11}, the benefit of maintaining tradition is E_{12}, and the average benefit is $\overline{E_1}$.

The benefits of technological innovation adopted by enterprises are:

$$E_{11} = y[(P_i - C_i)Q - I] + (1 - y)[\lambda(P_i - C_i)Q - I] \quad (1)$$

The benefits of enterprises not adopting technological innovation are:

$$E_{12} = y(\lambda(P_t - C_t)Q) + (1 - y)(P_t - C_t)Q \quad (2)$$

Then the average return of the enterprise adopting the mixed strategy is:

$$\overline{E_1} = xE_{11} + (1 - x)E_{12} \quad (3)$$

The income of enterprises adopting technological innovation is E_{21}, the income of maintaining tradition is E_{22}, and the average income is $\overline{E_2}$.

The benefits of consumers purchasing innovative products are:

$$E_{21} = xQV_i + (1 - x)\lambda(V_t - F)Q \quad (4)$$

The benefits of consumers purchasing traditional products are:

$$E_{22} = x(\lambda Q(V_i - F)) + (1 - x)QV_t \quad (5)$$

Then the average payoff for the consumer to adopt a mixed strategy is:

$$\overline{E_2} = yE_{21} + (1 - y)E_{22} \quad (6)$$

According to the Malthusian dynamic equation, if an individual employing a specific strategy achieves a return exceeding the group's average return, this strategy will progressively proliferate, leading to the formulation of the dynamic equation of replication for firms and consumers as follows:

$$F(x) = x(1 - x)(-I + \big((C_i + C_t - P_i - P_t)(\lambda - 1)y + (P_i - C_i)\lambda + C_t - P_t\big)Q) \quad (7)$$

$$F(y) = y(1 - y)(\big((1 - \lambda)(V_i + V_t) + 2\lambda F\big)Qx + (-V_t + \lambda V_t - \lambda F)Q) \quad (8)$$

EVOLUTIONARY STABILITY ANALYSIS

Evolutionary Stability Analysis of Enterprise Strategy

By setting the dynamic equation of the enterprise as $F(x) = 0$, we obtain $x = 0$, $x = 1$, $y^* = \frac{\lambda Q(C_i - P_i) - Q(C_t - P_t) + I}{(C_i - P_i + C_t - P_t)(\lambda - 1)Q}$.

When $y = y^*$, for any rate of x, $F(x)$ remains constant at 0, indicating that the probability of consumers employing the strategy of “purchasing innovative products” is y^*. There is no distinction between “adopting innovation” and “maintaining tradition”, and the evolutionary game remains constant. The current dynamic trend and stability of enterprise group replication are illustrated in Figure 1(a).

When $y \neq y^*$, by setting $F(x) = 0$, stability is achieved when $x = 0$ or $x = 1$. Taking the derivative of $F(x)$, then

$$\frac{dF(x)}{dx} = (1 - 2x)(-I + \big((C_i + C_t - P_i - P_t)(\lambda - 1)y + (P_i - C_i)\lambda + C_t - P_t\big)Q) \quad (9)$$

The evolutionary stable strategy shall meet the following condition: $\frac{dF(x)}{dx} < 0$

1. When $y^* < 0$, it holds that $y > y^*$. In this case, $x = 1$ represents an evolutionarily stable strategy, indicating that the enterprise's stable strategy is to adopt innovation. Figure 1(b) shows the current dynamic trend and stability of enterprise group replication.
2. When $y^* > 1$, it holds that $y < y^*$. In this case, $x = 0$ represents an evolutionarily stable strategy, indicating that the enterprise's stable strategy is to maintain tradition. Figure 1(c) shows the current dynamic trend and stability of enterprise group replication.
3. When $0 < y^* < 1$, if $y < y^*$, then $\frac{dF(x)}{dx}|_{x=0} < 0$ and $\frac{dF(x)}{dx}|_{x=1} > 0$, indicating that $x = 0$ is an evolutionary stable strategy.

When the proportion of consumers choosing the strategy of "purchasing innovative products" is less than y^*, enterprises gradually shift from "adopting innovation" to "maintaining tradition" strategy, and eventually stabilize on "maintaining tradition".

If $y > y^*$, then $\frac{dF(x)}{dx}|_{x=0} > 0$ and $\frac{dF(x)}{dx}|_{x=1} < 0$, demonstrating that $x = 1$ is an evolutionarily stable strategy.

When the proportion of consumers choosing the strategy of "purchasing innovative products" is greater than y^*, the enterprise group gradually shifts from "maintaining tradition" to "adopting innovation" strategy, and finally stabilizes on "adopting innovation". Figure 1(d) illustrates the current dynamic trend and stability of enterprise group replication.

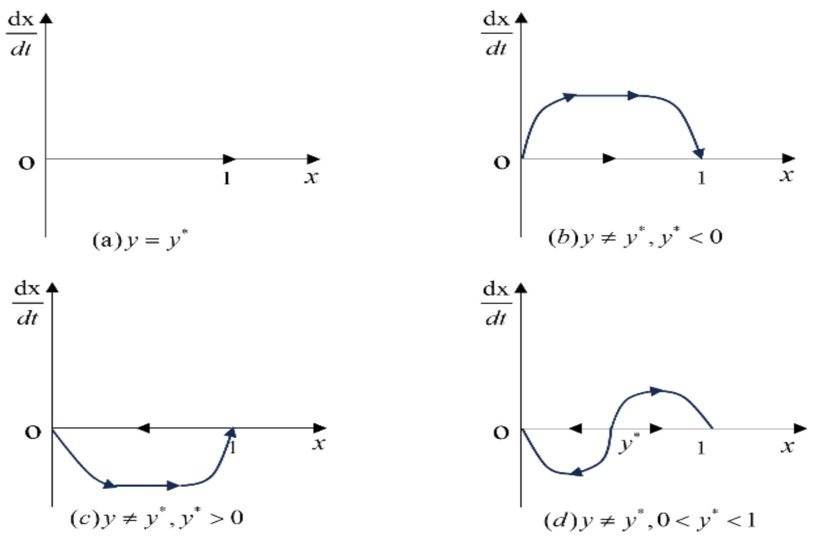


Figure 1: Enterprise Population Replication Dynamic Phase Diagram

Evolutionary Stability Analysis of Consumer Strategies

By setting the consumer's replication dynamic equation as $F(y) = 0$, we obtain $y = 0$, $y = 1$, and $x^* = \frac{V_t(1-\lambda)+\lambda F}{(1-\lambda)(V_i+V_t)+2\lambda F}$. When $x = x^*$, $F(y) = 0$ holds for any ratio of y. This indicates that when the probability of the enterprise choosing the "adopting innovation" strategy is x^*, there is no distinction between consumers selecting the “purchasing innovative products” strategy and the “purchasing traditional products” strategy. The evolutionary game is in a stable equilibrium. Figure 2 (a) shows the current dynamic trend and stability of consumer group replication.

When $x \neq x^*$, by setting $F(y) = 0$, stability is achieved when $y = 0$ or $y = 1$. Taking the derivative of $F(y)$, then

$$\frac{dF(y)}{dy} = (1-2y)(\big((1-\lambda)(V_i + V_t) + 2\lambda F\big)Qx + (-V_t + \lambda V_t - \lambda F)Q) \tag{10}$$

The evolutionary stable strategy shall meet the following conditions: $\frac{dF(y)}{dy} < 0$

1. When $x^* < 0$, it holds that $x > x^*$. In this case, $y = 1$ represents an evolutionarily stable strategy, indicating that the consumer’s stable strategy is to buy innovative products. Figure 2(b) shows the current dynamic trend and stability of consumer group replication.
2. When $x^* > 1$, it holds that $x < x^*$. In this case, $y = 0$ represents an evolutionarily stable strategy, indicating that the consumer’s stable strategy is to buy traditional products. Figure 2(c) shows the current dynamic trend and stability of consumer group replication.
3. When $0 < x^* < 1$, if $x < x^*$, then $\frac{dF(y)}{dy}|_{y=0} < 0$ and $\frac{dF(y)}{dy}|_{y=1} > 0$, indicating that $y = 0$ is an evolutionary stable strategy.

When the proportion of enterprises choosing the strategy of " adopting innovation " is less than x^*, consumers gradually shift from "purchasing innovative products" to "purchasing traditional products" strategy, ultimately stabilizing on the latter.

If $x > x^*$, then $\frac{dF(x)}{dx}|_{y=0} > 0$ and $\frac{dF(x)}{dx}|_{x=1} < 0$, indicating that $y = 1$ is an evolutionarily stable strategy.

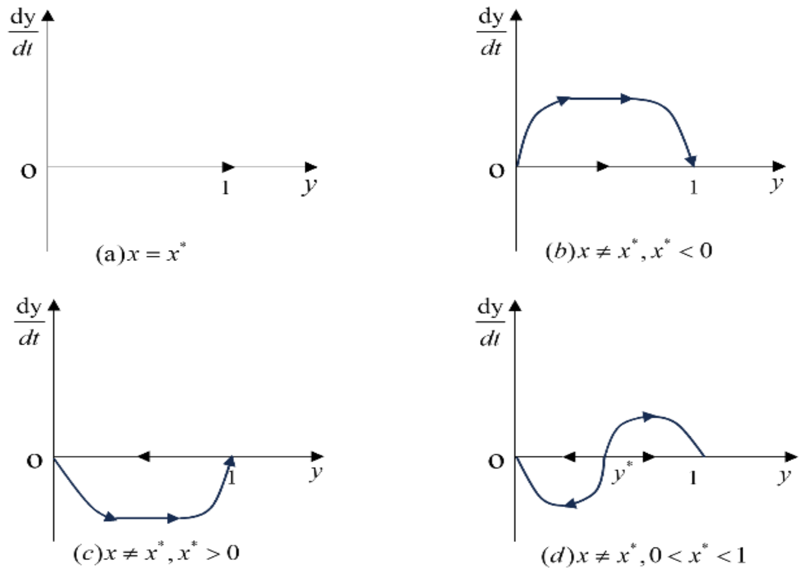


Figure 2: Consumer Population Replication Dynamic Phase Diagram

When the proportion of enterprises choosing the strategy of "purchasing innovative products" is greater than y^*, the enterprise group gradually shifts from "maintaining tradition" to "adopting innovation" strategy, and finally stabilizes on "adopting innovation". Figure 2(d) shows the current dynamic trend and stability of enterprise group replication.

Evolutionary Stability Analysis of Two-Strategy Games

Equation (11) is obtained by combining the replicator dynamic equations of enterprises and consumers, which can be used to describe the group evolution of enterprises and consumers.

$$\begin{cases} F(x) = x(1-x)(-I + \big((C_i + C_t - P_i - P_t)(\lambda - 1)y + (P_i - C_i)\lambda + C_t - P_t\big)Q) \\ F(y) = y(1-y)(\big((1-\lambda)(V_i + V_t) + 2\lambda F\big)Qx + (-V_t + \lambda V_t - \lambda F)Q) \end{cases} \tag{11}$$

Let $F(x) = 0$ and $F(y) = 0$, five equilibrium points are obtained: $E_1(0,0)$, $E_2(0,1)$, $E_3(1,0)$, $E_4(1,1)$, and $E_5(x^*,y^*)$, where $0 \le x^*$, $y^* \le 1$, $x^* = \frac{V_t(1-\lambda)+\lambda F}{(1-\lambda)(V_i+V_t)+2\lambda F}$, and $y^* = \frac{\lambda Q(C_i-P_i)-Q(C_t-P_t)+I}{(C_i-P_i+C_t-P_t)(\lambda-1)Q}$. The local stability analysis method for equilibrium points, as proposed by Federman (1991), determines the stability of these points through the analysis of the Jacobian matrix of the system (Xiao and Wang, 2017). The Jacobian matrix for the game system is represented by equation (12):

$$J = \begin{bmatrix} \frac{\partial F(x)}{\partial x} & \frac{\partial F(x)}{\partial y} \\ \frac{\partial F(y)}{\partial x} & \frac{\partial F(y)}{\partial y} \end{bmatrix} \tag{12}$$

$$= \begin{bmatrix} (1-2x)(-I + \big((C_i + C_t - P_i - P_t)(\lambda - 1)y + (P_i - C_i)\lambda + C_t - P_t\big)Q) & x(x-1)Q(1-\lambda)(C_i - P_i + C_t - P_t) \\ y(1-y)\big((V_i + V_t)Q + \lambda Q(2F - V_i - V_t)\big) & (1-2y)(\big((1-\lambda)(V_i + V_t) + 2\lambda F\big)Qx + (-V_t + \lambda V_t - \lambda F)Q) \end{bmatrix}$$

The determinant and trace of the Jacobian matrix at each equilibrium point are shown in Table 3.

Table 3: Determinant and Trace of Jacobian Matrix

Local equilibrium point	$Det(J)$	$Tr(J)$
$(0,0)$	$[(C_t - P_t)Q - I - \lambda Q(C_i - P_i)] * [-QV_t - \lambda Q(F - V_t)]$	$(C_t - P_t)Q - I - \lambda Q(C_i - P_i) - QV_t - \lambda Q(F - V_t)$
$(0,1)$	$[\lambda Q(C_t - P_t) - Q(C_i - P_i) - I] * [QV_t + \lambda Q(F - V_t)]$	$\lambda Q(C_t - P_t) - Q(C_i - P_i) - I + +QV_t + \lambda Q(F - V_t)$
$(1,0)$	$[I - (C_t - P_t)Q + \lambda Q(C_i - P_i)] * [QV_i + \lambda Q(F - V_i)]$	$I - (C_t - P_t)Q + \lambda Q(C_i - P_i) + QV_i + \lambda Q(F - V_i)$
$(1,1)$	$[I + Q(C_i - P_i) - \lambda Q(C_t - P_t)] * [-QV_i - \lambda Q(F - V_i)]$	$I + Q(C_i - P_i) - \lambda Q(C_t - P_t) - QV_i - \lambda Q(F - V_i)$
(x^*, y^*)	$-[x^*(x^* - 1)Q(1-\lambda)(C_i - P_i + C_t - P_t)] * [y^*(1-y^*)\big((V_i + V_t)Q + \lambda Q(2F - V_i - V_t)\big)]$	0

If the equilibrium points Jacobian matrix determinant $Det(J) > 0$, and the trace $Tr(J) < 0$, then it can be judged that the corresponding equilibrium point has the property of asymptotic stability, which is called ESS point. If $Det(J) > 0$ and $Tr(J) > 0$, then it can be judged that the corresponding equilibrium point is unstable. If $Det(J) < 0$ and $Tr(J) = 0$ or when it is indeterminate, the corresponding equilibrium point can be judged to be a saddle point. This serves as the foundation for inferring the stability point and its associated system evolutionary state, as shown in Tables 4-7.

State ①: When $-(C_i - P_i)\lambda Q + (C_t - P_t)Q < I$ and $(C_t - P_t)\lambda Q - (C_i - P_i)Q > I$, the system has two stable points: $E_1(0,0)$ and $E_4(1,1)$. At this time, when consumers prefer innovation, the benefits of adopting innovation are higher than those of maintaining tradition. When consumers prefer tradition, the benefits of adopting innovation are lower than those of maintaining tradition. For enterprises, when consumers tend to buy innovative products, they usually choose to adopt technological innovation. When it is speculated that consumers tend to buy traditional products, they usually choose to keep traditional. After many games, the evolution of the system is stable in {enterprises adopt innovation, consumers buy innovative products} or {enterprises maintain tradition. When consumers purchase innovative products, the specific evolutionary stable point is related to their initial state and payment matrix. Figure 3 (a) shows the system evolution trajectory in state ①.

Table 4: Stability analysis under state ①

Equilibrium point	$Det(J)$	$Tr(J)$	Stability
$E_1(0,0)$	+	−	ESS
$E_2(0,1)$	+	+	Unstable
$E_3(1,0)$	+	+	Unstable
$E_4(1,1)$	+	−	ESS
$E_5(x^*, y^*)$	−	0	Saddle point

State ②: $-(C_i - P_i)\lambda Q + (C_t - P_t)Q > I$ and $(C_t - P_t)\lambda Q - (C_i - P_i)Q > I$, the stable point of the system is $E_4(1,1)$. At this time, whether consumers prefer innovation or tradition, the benefits of adopting innovation are higher than those of maintaining tradition. At the same time, from the payment matrix, we can see that consumers can get the highest value when the products they choose to buy are consistent with the products produced by enterprises. Therefore, based on the principle of maximizing benefits, enterprises will choose to adopt innovation, while consumers choose to buy innovative products. The system evolution trajectory in state ② is shown in Fig. 3 (b).

Table 5: Stability analysis in state ②

Equilibrium point	$Det(J)$	$Tr(J)$	Stability
$E_1(0,0)$	−	Not sure	Saddle point
$E_2(0,1)$	+	+	Unstable
$E_3(1,0)$	−	Not sure	Saddle point
$E_4(1,1)$	+	−	ESS

State ③: $-(C_i - P_i)\lambda Q + (C_t - P_t)Q < I$ and$(C_t - P_t)\lambda Q - (C_i - P_i)Q < I$, the stable point of the system is $E_1(0,0)$.At this time, whether consumers prefer innovation or tradition, the benefits of adopting innovation are lower than those of maintaining tradition. At the same time, from the payment matrix, we can see that consumers can get the highest value when the products they choose to buy are consistent with the products produced by enterprises. Therefore, based on the principle of maximizing benefits, enterprises will choose to maintain tradition, while consumers choose to buy traditional products. The system evolution trajectory in the state ③ is shown in Fig. 3 (c).

Table 6: Stability analysis in state ③

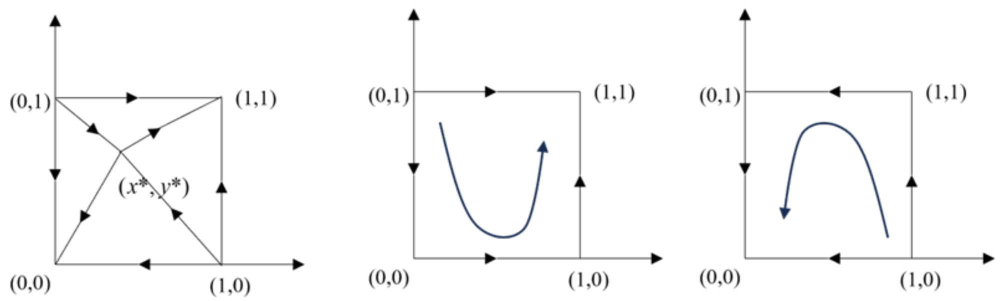
Equilibrium point	$Det(J)$	$Tr(J)$	Stability
$E_1(0,0)$	+	−	ESS
$E_2(0,1)$	−	Not sure	Saddle point
$E_3(1,0)$	+	+	Unstable
$E_4(1,1)$	−	Not sure	Saddle point

State ④: When $-(C_i - P_i)\lambda Q + (C_t - P_t)Q > I$ and$(C_t - P_t)\lambda Q - (C_i - P_i)Q < I$, we obtain $(C_i + C_t - P_i - P_t)(1-\lambda)Q > 0$.

However, based on the above assumptions, we know that $P_i > C_i$, $P_t > C_t$, and $0 < \lambda < 1$, which implies $(C_i + C_t - P_i - P_t)(1-\lambda)Q < 0$ always holds. Therefore, state ④ does not exist.

Table 7: Stability analysis in state ④

Equilibrium point	$Det(J)$	$Tr(J)$	Stability
$E_1(0,0)$	−	Not sure	Saddle point
$E_2(0,1)$	−	Not sure	Saddle point
$E_3(1,0)$	−	Not sure	Saddle point
$E_4(1,1)$	−	Not sure	Saddle point



(a) State ① (b) State ② (c) State ③

Figure 3: Dynamic phase diagram of the evolutionary game of the system

SIMULATION ANALYSIS

Initial Parameter Assignment

Given that the initial values of *x* and *y* are both 0.5. Combined with the actual situation, we refer to Li et al. (2021) and Zhang et al. (2019) to assign values to the other parameters, as presented in Table 8.

Table 8: Initial assignment of parameters

x	y	Q	P_i	P_t	C_i	C_t	V_i	V_t	I	λ	F
0.5	0.5	4000	8	5	3	2	4.5	2.5	100	0.4	40

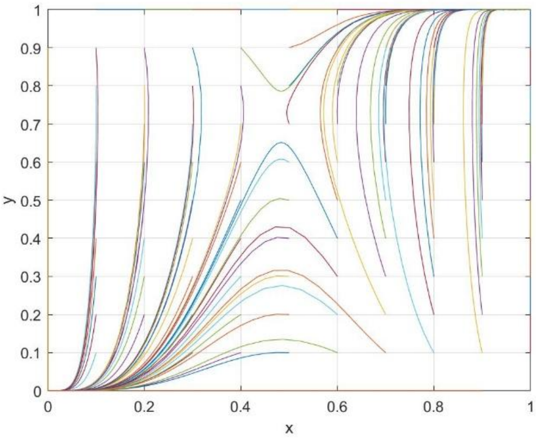


Figure 4: Evolution path diagram

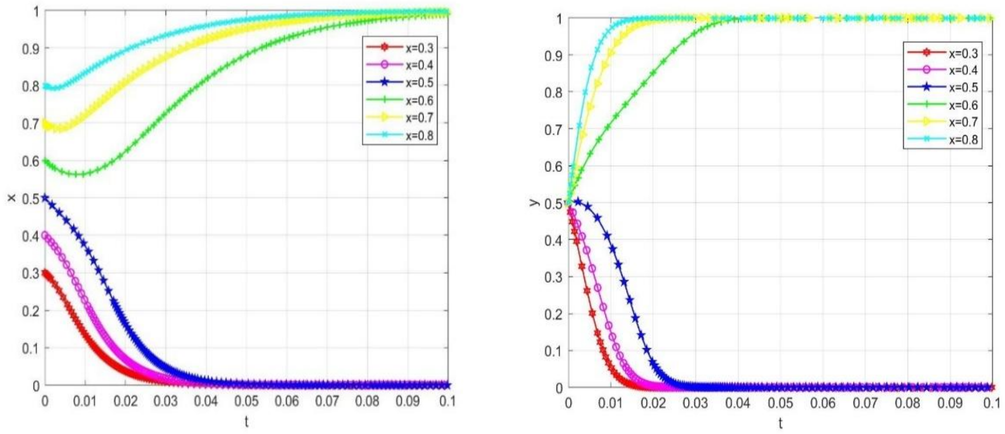
The initial assignment data is brought into the game model to evolve 20 times over time, and the evolution path graph is obtained as shown in Figure 4. The system evolution is stable at (0, 0) or (1, 1), that is, {Enterprises adopt innovation, Consumers purchase innovative products} or {Enterprises maintain tradition, Consumers purchase innovative products}.

Impact of Initial Probability on the Evolution Strategy of the System

It can be seen from Figure 5 that when the values of the initial probability (*x*) are 0.3, 0.4, and 0.5. The system has evolved to the state that enterprises maintain tradition and consumers buy traditional products, and technological innovation has not been diffused. However, when the value of the initial probability increases to 0.6, 0.7, and 0.8, the system evolves to the state that enterprises adopt technological innovation and consumers buy innovative products, and technological innovation can be successfully diffused.

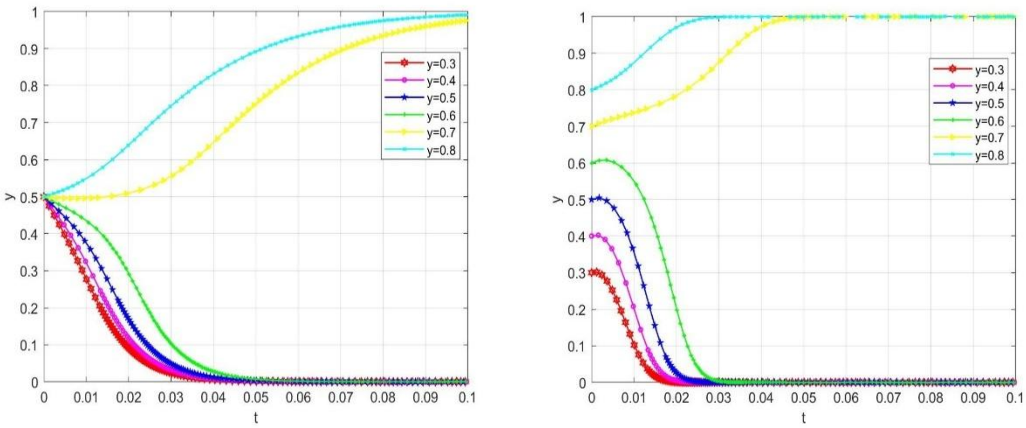
It can be seen from Figure 6 that when the values of the initial probability (*y*) are 0.3, 0.4, 0.5 and 0.6, the system has evolved to the state that enterprises maintain tradition and consumers buy traditional products, and technological innovation has not been diffused.

However, when the value of the initial probability increases to 0.7 and 0.8. The system evolves to the state that enterprises adopt technological innovation and consumers buy innovative products, and technological innovation can be successfully diffused.



(a) Enterprise adoption strategy **(b) Consumer purchase strategy**

Figure 5: Impact of initial probability x on system evolution strategies



(a) Enterprise adoption strategy **(b) Consumer purchase strategy**

Figure 6: Impact of initial probability *y* on system evolution strategies

Figures 5 and 6 indicate that the critical value of the initial probability *x* is situated between [0.5, 0.6]. When *x* is below this critical value, an increase in *x* results in a slower convergence of enterprises and consumers towards 0, implying that the system requires more time to reach the stable state {maintaining tradition, purchasing traditional products}. Conversely, when *x* exceeds the critical value, an increase in *x* leads to a quicker convergence of enterprises and consumers towards 1, indicating a decreasing time required to attain a steady state {adopting innovation, purchasing traditional products}.

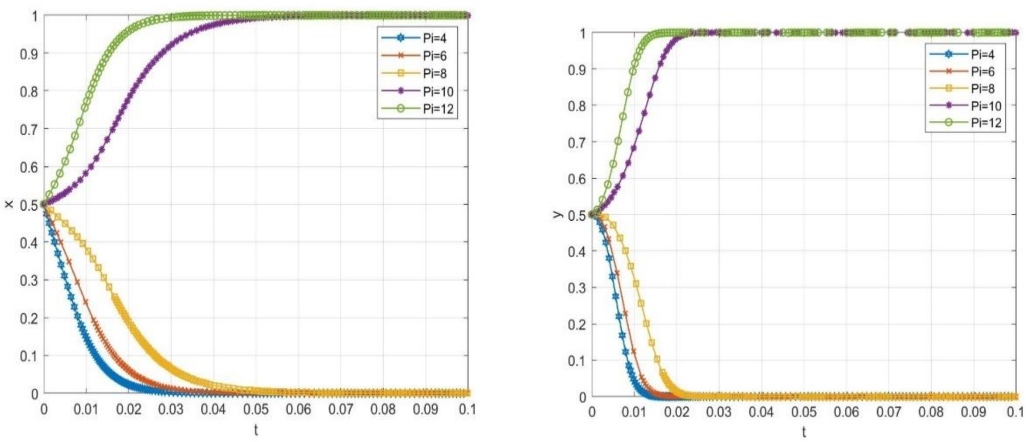
The initial probability *y* has a critical value that falls within the range of [0.6, 0.7]. Similar to the alteration of the initial probability *x*, when *y* is below the critical threshold, an increase in y results in enterprises and consumers converging to 0 at a more gradual pace, meaning that the system requires an extended duration to get the stable state {maintaining tradition, purchasing traditional products}. When y exceeds the critical value, as y increases, enterprises and consumers converge to 1 at an accelerating rate, meaning the system requires progressively less time to attain the steady state {adopting innovation, purchasing traditional products}.

Impact of Revenue and Cost on System Evolution Strategy

(1) Price of Innovative Products (P_i)

Figure 7(a) indicates that an increase in the price of the innovative product results in a shift in the enterprise's strategy from "maintaining tradition" to "adopting innovation". When the value of P_i is 4, 6 and 8, x converges to 0, indicating that the enterprise's final choice is to "maintaining tradition". Additionally, as P_i increases, the rate of convergence of x to 0 decreases. For example, when P_i rises from 6 to 8, the evolution time extends from 0.035 to 0.055. However, when the value of P_i is 10 or 12, x converges to 1, signifying that the final choice of the enterprise is to "adopting innovation". In this case, as P_i increases, the speed of evolution of x accelerates. For example, when P_i increases from 10 to 12, the evolution time decreases from 0.06 to 0.03. This is because revenue is equal to price minus cost, and out of the principle of profit maximization, enterprises will choose to "adopting innovation" strategy only if the incremental revenue generated by the product innovation is greater than the cost input.

From Figure 7(b), it can be observed that the consumers' strategy choice shifts from "purchasing traditional products" to "purchasing innovative products" as P_i increases. When the value of P_i is 4, 6, or 8, y converges to 0, meaning consumers ultimately choose to "purchasing traditional products", and the higher the value of P_i, the slower y evolves to 0. However, when the value of P_i is 10 or 12, y converges to 1, meaning consumers ultimately choose to "purchasing innovative products". In this case, the higher the value of P_i, the faster the evolution of y.



(A) Enterprise adoption strategy **(B) Consumer purchase strategy**

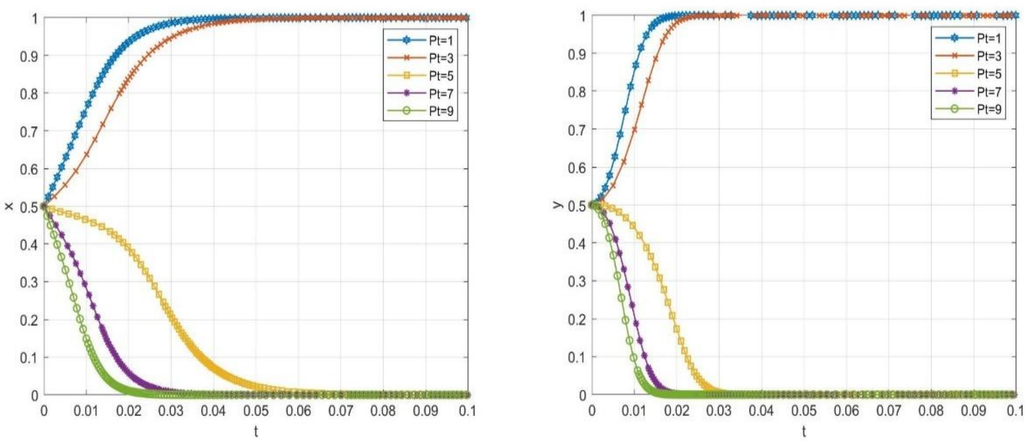
Figure 7: Impact of innovative product revenue on system evolution strategies

To sum up, the critical value of P_i is located at [8,10], and the value of P_i is greater than critical value of 10 and 12, and the technological innovation can successfully realize the diffusion, and the time required for diffusion decreases with the increase of R_i.

(2) Price of Traditional Products (P_t)

As can be seen from Figure 8 (a), as the price of the traditional product decreases, the strategic choice of enterprises will shift from "maintaining tradition" to "adopting innovation". When the value of P_t is 1 and 3, x converges to 1, indicating that the final choice of the enterprise is to "adopting innovation", and the larger the value of P_t, the slower x evolves to 1. However, when the value of P_t is 5, 7 and 9, x converges to 0, meaning that the final choice of the enterprise is to "maintaining tradition". In this case, the larger the value of P_t, the faster x evolves to 0. For example, when P_t increasing from 5 to 7, the evolution time is shortened from 0.06 to 0.025. This occurs because when the price of a traditional product is sufficiently elevated, enterprises perceive that the implementation of technological innovation will not yield additional advantages and are inclined to uphold traditional practices.

As can be seen in Figure 8(b), consumers' strategic choices also shift from “purchasing traditional products” to “purchasing innovative products” as the price of traditional products decreases. When the value of P_t is 1 and 3, y converges to 1, indicating that the final choice of consumers is "purchasing innovative products", and the larger the value of P_t, the slower x evolves to 1. However, when the value of is 5, 7 and 9, y converges to 0, meaning that the final choice of consumers is to "purchasing traditional products". At this point, the larger the value of P_t, the faster x evolves to 0. For example, when P_t increases from 5 to 7, the evolution time is shortened from 0.036 to 0.015.



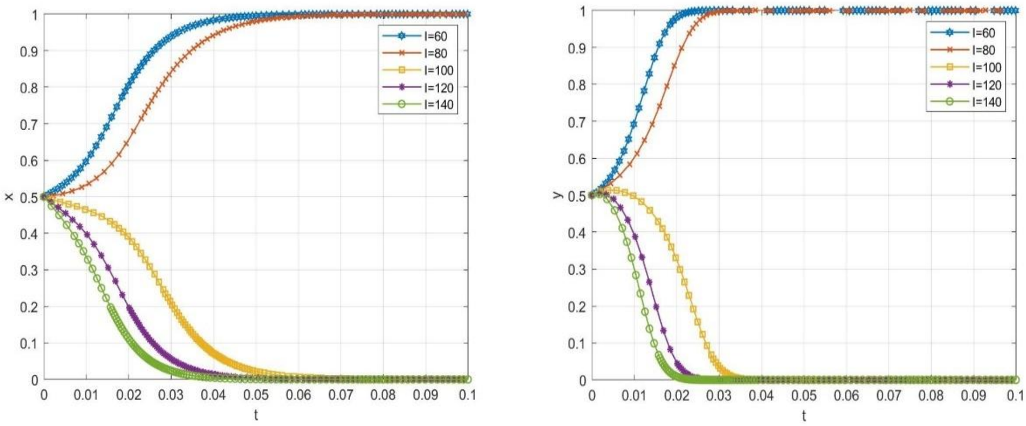
(a) Enterprise adoption strategy **(b) Consumer purchase strategy**

<u>Figure 8</u>: Impact of traditional product revenue on system evolution strategies

In summary, the critical value of P_t is situated within the range of [3,5]. When P_t is below the critical values of 1, 2, or 3, technological innovation can effectively achieve diffusion, and the time necessary for diffusion diminishes as P_t decreases.

(3) Cost Input (I)

It can be seen from Figure 9(a) that the increase in the expected investment in adopting technological innovation will reduce the enthusiasm of enterprises to adopt technological innovation. When the value of I is 60 or 80, *x* converges to 1, indicating that the final choice of the enterprise is to "adopting innovation", and the smaller the value of I, the faster *x* evolves. However, when the value of *I* is 100, 120 and 140, *x* converges to 0, meaning the enterprise ultimately choose to "maintaining tradition". At this point, the higher the value of I, the faster the evolution of *x*. According to the cost-benefit principle, enterprises evaluate associated costs and benefits when making decisions, thereby avoiding scenarios where benefits are less than anticipated costs. If the investment is excessively high, it does not align with the interests of the enterprise, leading the enterprise to ultimately opt for maintaining the status quo rather than adopting technological innovation. Figure 9(b) shows a negative correlation between consumers' motivation to purchase innovative products and the anticipated inputs. When the value of *I* is 60 or 80, *y* converges to 1, indicating that the final choice of consumers is “purchasing innovative products”, and the smaller the value of *I*, the faster the evolution of *y*. When *I* is 100, 120, or 140, *y* converges to 0, indicating that consumers have decided to "purchasing traditional products". At this point, the higher *I*, the faster *y* is evolving.



(a) Enterprise adoption strategy **(b) Consumer purchase strategy**

<u>Figure 9</u>: Impact of the projected cost of adopting innovation on system evolution strategies

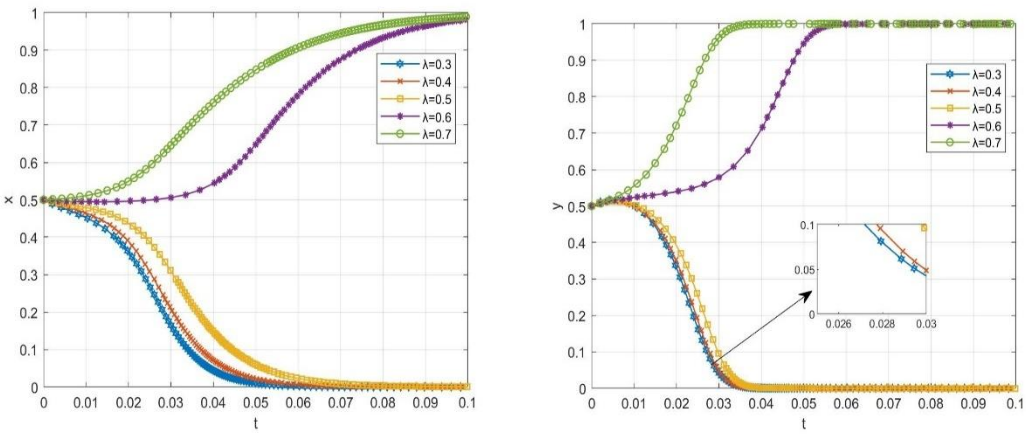
Overall, the critical value of *I* lies between [190, 240]. When the value of *I* is below this critical threshold, technological innovation can successfully diffuse, and the time required for diffusion decreases as *I* decreases.

Impact of Consumer Characteristics on System Evolution Strategy

(1) Consumer Acceptance (λ)

Figure 10(a) indicates that enterprise enthusiasm for adopting technological innovation is positively correlated with consumer acceptance. When λ is 0.6 or 0.7, *x* converges to 1, meaning the enterprise ultimately choose to “adopting innovation”, and the larger the value of λ, the faster the evolution of x. However, when λ is 0.3, 0.4, or 0.5, x converges to 0, meaning the enterprise ultimately choose to “adopting innovation”. In this case, the larger the value of λ, the slower the evolution of x. For example, when λ increases from 0.4 to 0.5, the evolution time increases from 0.055 to 0.075. This is because λ represents the consumer's acceptance of products that do not meet their psychological expectations. The large λ is, the more likely traditional consumers are to change their minds and switch to purchasing innovative products. As a result, enterprises adopting technological innovation can gain more benefits.

From Figure 10(b), it can also be observed that consumer enthusiasm for purchasing innovative products increases as consumer acceptance grows. When λ is 0.6 or 0.7, y converges to 1, meaning consumers ultimately choose to “purchasing innovative products”. Additionally, a higher value of λ results in a more rapid evolution of y. For instance, when λ increases from 0.6 to 0.7, the evolution time decreases from 0.06 to 0.032. However, when λ is 0.3, 0.4 or 0.5, y converges to 0, meaning consumers ultimately choose to “purchasing traditional products”. In this case, the larger the value of λ, the slower the evolution of y.



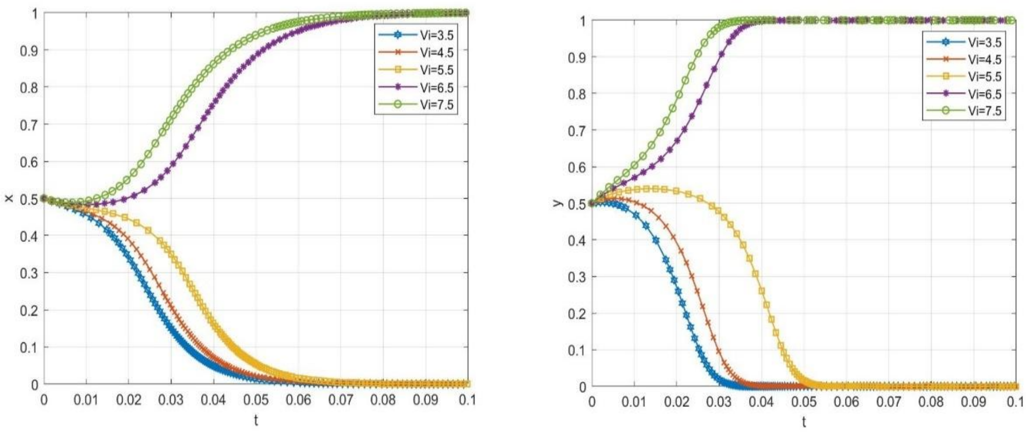
(a) Enterprise adoption strategy **(b) Consumer purchase strategy**

Figure 10: Impact of consumer acceptance on system evolution strategies

In summary, the critical value of λ is located at [0.2, 0.4], when the value of λ is taken higher than the critical value, the technological innovation can successfully realize the diffusion, and the time required for diffusion decreases as λ increases.

(2) Perceived Value of Innovative Products (V_i)

Perceived value refers to consumers' subjective perception and evaluation of the use value of products. It can be seen from Figure 11 (b) that the probability of consumers "purchasing innovative products" is highly sensitive to the perceived value of innovative products. An increase in V_i boosts consumers' willingness to purchase innovative products. When V_i is relatively low, such as 3.5, 4.5, and 5.5, consumers' satisfaction with innovative products is low. They perceive that purchasing and using these products does not offer greater utility, thus they tend to choose traditional products with similar performance. In this case, y converges to 0, meaning the final consumer choice is to “purchasing traditional products”. Moreover, as V_i increases, the speed of evolution toward 0 slows down. For instance, when V_i decreases from 5.5 to 4.5, the evolution time reduces from 0.05 to 0.35. However, when V_i increases to 6.5 or 7.5, consumers' satisfaction with innovative products rises, and they perceive that innovative products bring high utility. As a result, even if the price is higher, they are willing to choose innovative products. In this case, y converges to 1, meaning the final consumer choice is to “purchasing innovative products”. The larger V_i gets, the more rapid the evolution of y. From Figure 11 (a), we can see that the probability of "adopting innovation" is also sensitive to the perceived value of innovative products. When V_i is relatively low, such as 3.5, 4.5, and 5.5, x converges to 0, meaning the enterprise ultimately chooses to "maintaining tradition". As V_i increases, the speed at which x evolves to 0 gradually slows down. For example, when V_i decreases from 5.5 to 4.5, the evolution time reduces from 0.06 to 0.055. When V_i increases to 6.5 or 7.5, x converges to 1, meaning the enterprise ultimately chooses to “adopting innovation”. At this point, as V_i increases, the speed of evolution of x accelerates. This behavior is consistent with real-world conditions, as enterprises make decisions based on the principle of maximizing their own interests, which aligns with market demand. The stronger consumers' willingness to purchase innovative products, the more likely enterprises are to invest in adopting innovation.



(a) Enterprise adoption strategy **(b) Consumer purchase strategy**

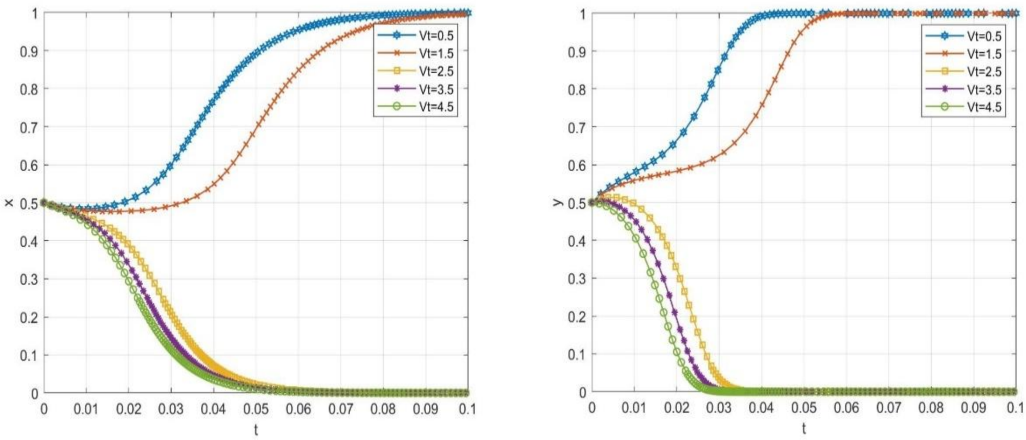
Figure 11: Impact of consumers' perceived value of innovative products on system evolution strategies

To sum up, the critical value of is V_i located at [5.5,6.5], and when the value of V_i exceeds this critical value, technological innovation can be successfully diffused. And the time required for diffusion decreases with the increase of V_i.

(3) Perceived Value of Traditional Products (V_t)

As shown in Figure 12, both the probability x of enterprises "adopting innovation" and the probability y of consumers "purchasing innovative products" are highly sensitive to the perceived value of traditional products, and both exhibit a significant negative correlation. When V_t is relatively high, such as 2.5, 3.5, and 4.5, consumers perceive that traditional products can meet their existing needs well and have high utility value. Therefore, innovations in product performance, functionality, and usage methods have limited appeal, making consumers more inclined to purchase traditional products. This is reflected in the graph, where over time, *y* ultimately converges to 0. Enterprise decisions are closely related to consumer demand; only by aligning with market demand can enterprises maximize their own benefits. Therefore, when consumer demand favors traditional products, enterprises will choose the "maintain the original model" strategy, as shown in Figure 12(a), where *x* ultimately converges to 0.

When V_t decreases to 0.5 or 1.5, consumers perceive that traditional products no longer meet their current needs and have lower utility. As a result, they are eager to purchase more practical and novel innovative products. At the same time, enterprises, aiming to maximize their benefits, will adjust their strategies in response to consumer purchasing demands. As a result, they typically adopt the "adopting innovation" strategy, introducing new technologies and upgrading existing products. As shown in Figure 12(b), both *x* and *y* ultimately converge to 1.



(a) Enterprise adoption strategy **(b) Consumer purchase strategy**

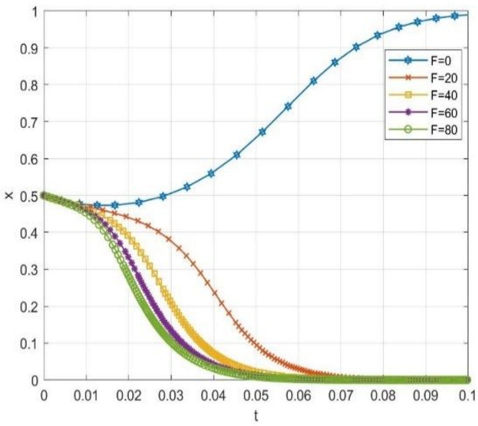
<u>Figure 12</u>: Impact of consumers' perceived value of traditional products on system evolution strategies

To sum up, the critical value of V_t is located at [1.5, 2.5], when the value of V_t is lower than critical value, technological innovation can successfully achieve diffusion. And the time required for diffusion decreases with the decrease of V_t.

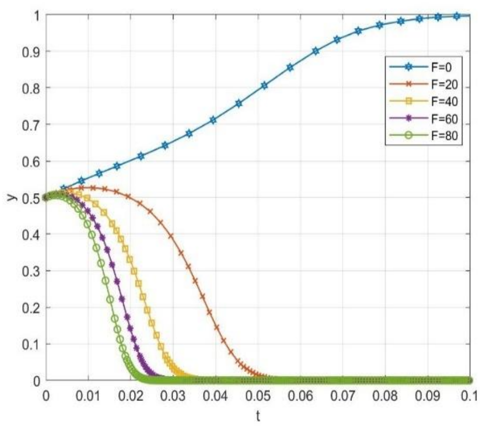
(4) Perceived Loss (F)

Frefers to the perceived loss of consumers when the demand for products does not match the supply of the market. It can be seen from Figure 13 (a) that the enthusiasm of enterprises to adopt technological innovation is negatively correlated with perceived loss. When the value of *F* is 0, *x* converges to 1, that is, the final choice of the enterprise is to "adopting innovation". However, when the value of *F* is 20, 40, 60 and 80, *x* converges to 0, that is, the final choice of the enterprise is to " maintaining tradition". At this time, the larger the value of *F*, the faster the evolution of *x*. For example, when the value of *F* increases from 20 to 40, the evolution time decreases from 0.07 to 0.05.

As shown in Figure 13(b), consumers' enthusiasm for purchasing innovative products also decreases as perceived loss increases. When *F* is 0, *y* converges to 1, meaning consumers ultimately choose to "purchasing innovative products". However, when *F* takes values of 20, 40, 60, or 80, *y* converges to 0, meaning consumers ultimately choose to "purchasing traditional products". At this point, the larger the value of *F*, the faster the evolution of *y*. For instance, when *F* increases from 20 to 40, the evolution time decreases from 0.05 to 0.03.



(a) Enterprise adoption strategy



(b) Consumer purchase strategy

Figure 13: Impact of perception loss on system evolution strategies

In summary, the critical value of *F* is situated at [0,20]. When the value of *F* is below this critical threshold, technological innovation can effectively achieve diffusion, and the time necessary for diffusion diminishes as *F* decreases.

CONCLUSION

This study develops an evolutionary game model to analyze the diffusion of technological innovation from both supply and demand perspectives, covering enterprise production and consumer purchasing behavior. It explores the strategic choices of enterprises regarding innovation adoption and consumers' selection of innovative products. Using MATLAB simulations, we examine how market factors, such as revenue, costs, and consumer characteristics, influence the strategic decisions of both enterprises and consumers.

The results show that: (1) Revenue and cost factors affect the strategic choices of enterprises and consumers {Adopt innovations, purchase innovative products}. The price of the innovative product is positively driven, while the price of the traditional product and the expected cost inputs are negatively correlated. (2) Consumer characteristics factor effectively portrays the psychological process of consumer innovation consumption in the market. Consumer acceptance and the perceived value of innovative products promote the diffusion of technological innovation, and the larger the value of both, the more companies and consumers tend to choose the strategy of {Adopt innovation, purchase innovative products}; the perceived value of traditional products and the perceived loss inhibit the diffusion of technological innovation, and the larger the value of both, the more enterprises and consumers tend to choose the strategy of {Maintain tradition, purchase traditional products}.

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