

Analysis of the Evolutionary Game of Enterprise Cooperation Behavior on Green Technology Innovation from the Perspective of High-Tech Industry Agglomeration

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Abstract: This present work develops a dynamic evolutionary model concerning green innovation from a tripartite standpoint involving the authorities, company, ect. , and conducts computational experiments conducted via MATLAB 2018b. The results indicate that the willingness of the agents is the cornerstone of the stability of cooperative innovation in green innovation, whose benefits of cooperative innovation act as the primary catalyst for firms' participation in green technology innovation—a higher level of perceived benefits correlates with a stronger firms' enthusiasm for cooperative innovation. An appropriate level of authorities-imposed penalties can deter opportunistic behavior among enterprises. A reasonable coefficient for benefit distribution enables more sustained and effective cooperative innovation, thereby further promoting green technology innovation. Finally, corresponding practice-oriented recommendations are proposed.

Keywords: Green Technology Innovation; High-Tech Industry Agglomeration; Cooperative Innovation; Evolutionary Game

1. Introduction

As the economy enters a new phase of high-caliber growth, old-fashioned economic scales models contingent upon demographic dividends, resource endowments, and labor advantages have become increasingly unsustainable [1]. There is an urgent need to reduce environmental pollution and greenhouse gas emissions. Consequently, accelerating green development and steering technological innovation toward green technological innovation has become particularly important. Green technological innovation materializes green technologies and, through the translation of outcomes, facilitates a

balanced development between high-quality economic growth and ecological protection. However, green technological innovation faces not only long-term personnel and capital investments and the high risks inherent in technological R&D but also the positive externalities of environmental benefits. These factors create dilemmas for most enterprises engaged in projects of cooperative. Technology-intensive agglomeration, characterized by high added value, high returns, and a high concentration of technological factors, serves as a crucial foundation for promoting green technological breakthroughs by leveraging knowledge spillover effects and collaborative innovation network effects. Therefore, understanding how to harness the advantages of high-tech industrial agglomeration, grasp the intrinsic logic between the cooperation of enterprises within such agglomerations and green technological innovation, and design effective cooperation mechanisms is key to stimulating enterprises' vitality in green technological innovation.

Relevant research can be broadly categorized into two areas. The first concerns cooperative innovation. In early studies on innovation cooperation, Fusfeld et al. [2] categorized industrial cooperative innovation in the United States into three types: activities supporting non-competitive industries, pre-competitive activities supporting high-tech and research-intensive industries, and activities supporting technology bases in regulated industries. Belderbos et al. [3] assessed the effects of cooperative innovation on firm performance through two major performance indicators: labor productivity and productivity from innovative sales. Sarpong, O et al. [4] found positive correlations between market-based cooperative innovation among firms and the entry of new corporate innovators, as well as between collaborations with scientific

and global partners and the entry of new-to-market innovators. Liu Lu et al. [5] proposed three forms of cooperative innovation and constructed corresponding game-theoretic models. The second area focuses on multi-agent game strategies for green technological innovation activities. Wang Dan et al. [6] employed evolutionary game theory and found that appropriately increasing government penalties facilitates collaborative innovation. Xie Nan et al. [7] argued that a stable equilibrium exists between firms and governments in green technological innovation.

In summary, existing literature has extensively examined green technological innovation and cooperative innovation. However, most studies focus primarily on agents such as financial institutions, governments, and the public. The following issues remain underexplored: whether close linkages exist among firms, between firms and governments, and across all three; the roles of government subsidies and regulatory penalties in shaping corporate cooperative innovation; and how firms select cooperative innovation strategies to maximize profits while promoting green technological innovation. These questions warrant further investigation. This paper aims to systematically address these issues.

2. Hypothesis and Construction of Evolutionary Gaming Framework for Participating Cooperative Firms from the Perspective of Advanced-Technology Industrial Agglomeration

2.1 Model Assumptions

Hypothesis 1 Assumptions regarding game strategy agents. Under natural conditions with no other influencing factors, it is assumed that the agents in the game are the government, Enterprise A, and Enterprise B, all of which are boundedly rational groups. The strategies adopted by these three agents depend on the benefits derived from the strategic outcomes; that is, they are “egoists” pursuing benefit maximization.

Hypothesis 2 The government’s behavioral strategy set is $T_1 = \{K_1 \text{ Encourage}, K_2 \text{ Not encourage}\}$. “Encourage” refers to the government supporting enterprises in green innovation by building talent teams, providing technical services, and offering rewards and subsidies. “Not encourage” means the government does not take any measures to

intervene in whether enterprises engage in green technological innovation. Enterprise A’s behavioral strategy set is $T_2 = \{E_1 \text{ Cooperate}, E_2 \text{ Not cooperate}\}$. “Cooperate” means Enterprise A cooperates with Enterprise B. “Not cooperate” means Enterprise A does not cooperate with Enterprise B, instead adopting traditional production methods without taking any measures to reduce energy consumption or environmental impact. Enterprise B’s behavioral strategy set is $T_3 = \{H_1 \text{ Cooperate}, H_2 \text{ Not cooperate}\}$. “Cooperate” means Enterprise B cooperates with Enterprise A, improving the efficiency of green technological innovation through means such as technological innovation and factor market segmentation, thereby reducing the competitiveness of enterprises that do not improve their green innovation efficiency. “Not cooperate” means Enterprise B does not cooperate with Enterprise A and continues to adopt traditional production methods.

Hypothesis 3: At the beginning of the game, the likelihood that the authorities encourage green technological innovation is v , and the likelihood that they do not encourage is $1-v$. The likelihood that Enterprise A elects to cooperate with Enterprise B is s , and the likelihood that it does not cooperate is $1-s$. The likelihood that Enterprise B elects to cooperate with Enterprise A is u , and the likelihood that it does not cooperate is $1-u$, where $0 \leq v \leq 1$, $0 \leq s \leq 1$, and $0 \leq u \leq 1$.

Hypothesis 4 Let R_1 be the revenue obtained by Enterprise A under the traditional production model; R_2 be the revenue obtained by Enterprise B under the traditional production model; and R be the total synergistic cooperation revenue between enterprises, with a being the revenue distribution coefficient for Enterprise A and $1-a$ being the revenue distribution coefficient for Enterprise B, satisfying $0 \leq a \leq 1$.

Hypothesis 5 Let the expenditure on cooperation between Enterprise A and Enterprise B be C_0 . When both enterprises adopt cooperative strategies, t is the cost distribution coefficient for Enterprise A, and $1-t$ is the cost distribution coefficient for Enterprise B, satisfying $0 \leq t \leq 1$. In cases where Enterprise A opts for cooperation and Enterprise B chooses to discontinue cooperation, Enterprise A and Enterprise B must allocate and pay the previously incurred cost C_0 , and the defaulting party, Enterprise B, must pay a penalty W while obtaining a corresponding benefit L_2 , and vice

versa [8].

Hypothesis 6 When the government actively encourages green technological innovation, it provides financial subsidies to cooperating enterprises. Let G_1 and G_2 be the subsidies provided by the government to Enterprise A and Enterprise B, respectively, for green technological innovation. The benefit to the

government from green technological innovation is E . Additionally, the government imposes penalties on enterprises that choose not to engage in cooperative green technological innovation. Let F be the total penalty amount. The symbols for the parameters are listed in Table 1.

Table 1. Parameter Symbols and Their Meanings

R_1	Revenue obtained by Enterprise A under the traditional production model
R_2	Revenue obtained by Enterprise B under the traditional production model
R	Revenue generated by green technological innovation between Enterprise A and Enterprise B
a	Distribution coefficient of revenue generated by cooperation between Enterprise A and Enterprise B
C	Cost incurred by Enterprise A and Enterprise B when adopting the green technological innovation production model
C_0	Cost already invested by enterprises during cooperation in the event of default
W	Penalty paid by an enterprise for terminating cooperation
L_1	Benefit obtained by Enterprise A from terminating cooperation and paying the penalty
L_2	Benefit obtained by Enterprise B from terminating cooperation and paying the penalty
G_1	Government subsidy for green technological innovation provided to Enterprise A
G_2	Government subsidy for green technological innovation provided to Enterprise B
E	Benefit obtained by the government from enterprises' clean technology innovation
r_1	Coefficient of benefit obtained by the government when Enterprise A engages in green technological innovation but Enterprise B does not participate in cooperation
r_2	Coefficient of benefit obtained by the government when Enterprise B engages in green technological innovation but Enterprise A does not participate in cooperation
F	Penalty imposed for enterprises not engaging in green technological innovation

2.2 Construction of the Tripartite Evolutionary Game Model

According to the gaming combinations among Enterprise A, Enterprise B, and the government, there are eight possible scenarios: (E_1 cooperation, H_1 cooperation, T_1 encouragement), (E_1 cooperation, H_1 cooperation, T_2 non-encouragement), (E_1 cooperation, H_2 non-cooperation, T_1 encouragement), (E_1 cooperation, H_2 non-cooperation, T_2 non-encouragement), (E_2 non-cooperation, H_1 cooperation, T_1 encouragement), (E_2 non-cooperation, H_1 cooperation, T_2 non-encouragement), (E_2 non-cooperation, H_2 non-cooperation, T_1 encouragement), and (E_2 non-cooperation, H_2 non-cooperation, T_2 non-encouragement). Based on the assumptions in Table 1, the strategy combinations and the corresponding payoff matrix are constructed, as shown in Table 2.

Table 2. Strategy Combinations and Payoff Matrix

Strategy combination	Payoff of Enterprise A	Payoff of Enterprise B	Payoff of Government
(E_1, H_1, T_1)	$R_1 + aR - tC + G_1$	$R_2 + (1-a)R - (1-t)C + G_2$	$-G_1 - G_2 + E$
(E_1, H_1, T_2)	$R_1 + aR - tC$	$R_2 + (1-a)R - (1-t)C$	E
(E_1, H_2, T_1)	$R_1 - tC_0 + W + G_1$	$R_2 - (1-t)C_0 - (C - C_0) - W + L_2 - F$	$-G_1 + R_1E + F$
(E_1, H_2, T_2)	$R_1 - tC_0 + W$	$R_2 - (1-t)C_0 - (C - C_0) - W + L_2$	r_1E
(E_2, H_1, T_1)	$R_1 - tC_0 - (C - C_0) - W + L_1 - F$	$R_2 - (1-t)C_0 + W + G_2$	$-G_2 + r_2E + F$
(E_2, H_1, T_2)	$R_1 - tC_0 - (C - C_0) - W + L_1$	$R_2 - (1-t)C_0 + W$	r_2E
(E_2, H_2, T_1)	$R_1 - F$	$R_2 - F$	$2F$
(E_2, H_2, T_2)	R_1	R_2	0

3. Evolutionary Gaming Framework of Green-Tech Innovation

3.1 Replicator Dynamic Equations of the Tripartite Evolutionary Game

The behaviors of firm A, firm B, and the authorities are interdependent, and the three

parties continuously evolve to achieve mutually beneficial cooperation. The replicator dynamic equations for the three parties are constructed. Let U_{11} , U_{12} , and U_1 denote the anticipated return of firm A choosing "cooperation", the anticipated return of choosing "non-cooperation", and the average expected payoff, respectively, where:

$$U_{11}=(R_1+a* R-t* C+G_1)* s* u+(R_1+a* R-t* C)* s* (1-u)+(R_1-t* C_0+W+G_1)* (1-y)* u+(R_1-t* C_0+W)* (1-s)* (1-u) U_{12} \\ = (R_1-t* C_0-C+C_0-W+L_1-F)* s* u+(R_1-t* C_0-C+C_0-W+L_1)* s* (1-u)+(R_1-F)* (1-y)* z+R_1* (1-s)* (1-u) \quad (1)$$

$$U_1=vU_{11}+(1-v)U_{12} \quad (2)$$

The evolutionary replication dynamics of A is as follows

$$F(v)=\frac{dv}{dt}=v(U_{11}-U_1)=v* (1-v)* [W-C_0* t+(F+G_1)* u+(C-C_0-L_1+R* a-C* t+2* C_0* t)* s] \quad (3)$$

When $u=\frac{-(W-C_0*t)-(C-C_0-L_1+R*a-C*t+2*C_0*t)s}{F+G_1}$, we

have $F(v)=0$. In this case, the strategy of Enterprise A is stable for any value of v . When $u<\frac{-(W-C_0*t)-(C-C_0-L_1+R*a-C*t+2*C_0*t)s}{F+G_1}$, then

$F(v)'|_{v=0}<0, F(v)'|_{v=1}>0$, meaning that $v=0$ represents the steady state. Otherwise, $v=1$ is the

$$F(y)=\frac{ds}{dt}=s(U_{21}-U_2)=s* (1-s)* [W-C_0+C_0* t+(F+G_2)* z+(C_0-L_2+R-R* a+C* t-2* C_0* t)* v] \quad (4)$$

The replicator evolutionary rule for the

$$F(u)=\frac{du}{dt}=u(U_{31}-U_3)=u* (1-u)* [2* F-(F+G_1)* v-(G_2+F)* s] \quad (5)$$

By synthesizing the evolutionary path equations $F(v)$, $F(s)$, and $F(u)$, a kinetic evolutionary system consisting of firm A, firm B, and the authorities can be constructed. When the expected payoffs of the three parties are consistent, the system reaches a stable equilibrium, and the equilibrium solutions of the system can be obtained.

Thus, the probability that Enterprise A engages in green technology innovation is obtained as $v^*=\frac{-(F+G_2)z-(W-C_0+C_0*t)}{C_0-L_2+R(1-a)+C*t-2C_0*t}$. Whether Enterprise

A adopts green technology innovation depends on several factors: the authorities's sanction on enterprise A for not engaging in green technology innovation, the authorities's monetary incentive to firm B for green technology innovation, the costs already incurred by enterprises during cooperation in the event of a breach, the liquidated damages paid by the enterprise for terminating cooperation, the benefits obtained by Enterprise B from receiving liquidated damages when it terminates cooperation, the benefits gained by both enterprises from adopting the clean-tech innovation production model, the distribution coefficient of the cooperative benefits between firm A and firm B, and the probability of the government encouraging green technology innovation.

Similarly, whether Enterprise B engages in clean-tech innovation is related to the authority's penalty on Enterprise B for not engaging in clean-tech innovation, the probability that firm A engages in clean-tech innovation, and the authority's subsidies to both firms that engage in clean-tech innovation.

Whether the government promotes

equilibrium point.

Similarly, let U_{21} , U_{22} , and U_2 denote the anticipated return of firm B choosing "cooperation", anticipated return of firm of choosing "non-cooperation", and the average anticipated return, respectively.

The evolutionary path equation of B is given by:

government can be expressed as:

clean-technology depends on the authority's subsidy to firm B for green technology innovation, the costs incurred by enterprises during cooperation in the event of a breach, the liquidated damages paid for terminating cooperation, the benefits obtained by Enterprise B from receiving liquidated damages upon termination, the benefits gained by both enterprises from the clean-tech innovation production model, the distribution coefficient of the cooperative benefits between firm A and firm B, and the probability that Enterprise A engages in green technology innovation [9].

If you have the complete and correct expression for v^* (including the denominator), I can revise the equation part accordingly.

3.2 Equilibrium Stability Analysis of the Game

An evolutionarily stable strategy (ESS) is denoted by S, under which the fitness of any mutant strategy S' is lower than that of SS. By letting $F(v)=0$, $F(s)=0$, and $F(u)=0$, and solving the system simultaneously, 13 equilibrium points are obtained. These include 8 pure strategy equilibria located on the demarcation $\{(v, s, u) | v=0,1; s=0,1; u=0,1\}$. The eigenvalues and stability determination of the steady-state solutions are presented in Table 3.

Table 3. Eigen-roots and Convergence Characteristics Determination of Stationary Points Solutions

steady-state solution	Sign of eigenvalues	Stability
$Q_1(v_1, 1, u_1)$	$(*, +, -)$	unstable
$Q_2(0, 0, 0)$	$(+, *, *)$	non-stable
$Q_3(1, 0, 0)$	$(*, -, *)$	non-stable

$Q_4(0,1,0)$	$(*,*,*)$	non-stable
$Q_5(0,0,1)$	$(-,*,*)$	non-stable
$Q_6(1,1,0)$	$(-,*,*)$	non-stable
$Q_7(1,0,1)$	$(*,-,*)$	non-stable
$Q_8(0,1,1)$	$(*,-,*)$	non-stable
$Q_9(1,1,1)$	$(+,*,*)$	non-stable
$Q_{10}(v2,0,u2)$	$(*,+,-)$	unstable
$Q_{11}(1,s1,u3)$	$(+,+,-)$	unstable
$Q_{12}(0,s2,u4)$	$(*,+,-)$	unstable

Note: For the signs of eigenvalues in parentheses, "*" indicates uncertainty (the sign could be positive or negative).

4. Strategic-Evolution Experiment and Numerical Modelling of Firm Cooperative Behavior on Clean-Tech Innovation under High-Tech Industrial Clustering

Based on the above replicator dynamic equations and stability conditions, and referring to the study of Bian Chenchu et al., a simulation analysis is conducted, yielding the stable point $Q_4(0,1,0)$. This indicates that under local governments' passive supervision, Enterprise A and Enterprise B adopt different strategies due to inconsistent benefits. When the net benefit of Enterprise A adopting green technology innovation is positive compared with adopting the traditional production mode, it ultimately chooses the "traditional production mode" strategy. In contrast, when the net benefit of Enterprise B adopting clean-tech innovation is positive compared with adopting the traditional production mode, it ultimately chooses the "green technology innovation" strategy. Based on this, this paper further adjusts relevant parameters to explore the core influencing factors that drive the system toward an ideal stable state [10].

4.1 Influence of Changes in Subject Willingness

When the government actively supports green technology innovation, the probability that both enterprises simultaneously choose collaborative innovation increases. Compared with the scenario where the government does not encourage green technology innovation, subsidies provided under cooperation reduce corresponding costs, while penalties constrain enterprises that opt for breach of contract without engaging in clean-tech innovation, thereby reducing the risks of such R&D efforts. When the willingness of both Enterprise A and Enterprise B to choose cooperative innovation is

0.5, the simulation examines the impact of changes in the Chinese government's willingness to actively encourage cooperative clean-tech innovation on the evolutionary results. The simulation results reveal that active government encouragement of cooperative green technology innovation promotes inter-enterprise collaboration.

4.2 Influence of Cooperative Innovation Benefits

Holding other parameters constant, the cooperative innovation benefit

R is assigned values of 100, 300, and 600, respectively. A rise in cooperative innovation dividends speed up the speed of enterprise clean-tech innovation.

As R increases, the probability of strict supervision by government regulatory authorities decreases. Therefore, the benefit obtained by firms from clean-tech innovation indirectly reflects the stability of the cooperative intention between the two enterprises: the greater the benefit, the more stable the cooperative intention. While cooperative innovation benefits prompt both enterprises to choose cooperative strategies, they also accelerate the government's evolution toward a non-regulatory strategy, which is crucial for reducing enterprise pressure and achieving green technology cooperative innovation.

4.3 Influence of Government Penalty Intensity

Holding other parameters constant, the government penalty intensity F is given values of 0, 20, and 40, in turn. During the evolution of each subject, before the cooperative adoption of green technology innovation stabilizes at 1, an increase in penalty intensity F leads to a decrease in the stringency of government supervision. As the cooperative adoption of green technology innovation gradually stabilizes at 1, the government's strict supervision rate gradually declines and stabilizes at 0. Enterprise A and Enterprise B continue to choose cooperation despite changes in penalty intensity. As penalty intensity increases, the speed of cooperation between the two enterprises accelerates, and they reach a stable state earlier. Thus, this trend indicates that government penalties promote enterprise cooperation, and enterprises are inclined to participate in green technology creativity when facing high penalties.

4.4 Influence of Benefit Distribution Coefficient

The benefit distribution coefficient is set as $\alpha=0.2, 0.5, 0.8$, respectively, to analyze the evolutionary outcomes of each subject. When $\alpha=0.5$, both parties tend to converge on the cooperative innovation strategy. When $\alpha=0.2$, Enterprise B converges more quickly to the cooperative strategy, while Enterprise A, receiving only a small portion of the benefits, converges more slowly, but ultimately chooses the cooperative strategy because it still gains benefits from cooperation. When $\alpha=0.8$, the speed at which Enterprise B converges to the cooperative strategy slows down. Thus, an unreasonable benefit distribution method affects the speed at which both enterprises reach green technology cooperative innovation, and establishing a reasonable benefit distribution mechanism is conducive to achieving and stabilizing green technology cooperative innovation.

5. Suggestions for Promoting Clean-Tech Innovation through Firm Cooperation from the Viewpoint of High-Tech Industry Clustering

First, enhance enterprise willingness to cooperate. For enterprises, leveraging the advantages of high-tech industry agglomeration, they should identify their own positioning within the group, form irreplaceability in terms of "cost-effectiveness" and "effective supply", and cooperate with complementary enterprises to compensate for their own deficiencies and strengthen cooperation willingness. For the government, it should optimize management systems and operational mechanisms in areas such as technology guidance, talent cultivation, and intellectual property rights, thereby further improving the environment for enterprise cooperative innovation. The government should fully play its coordinating role, guiding both technology agglomeration and talent agglomeration, thereby establishing a fixed reference for the development of clean-tech innovation.

Second, enhance the standard of joint innovation. To increase cooperative innovation benefits and reduce cooperative innovation costs during enterprise cooperative innovation, both parties can establish long-term stable cooperative relationships to enhance stability and continuity.

At the same time, leveraging the advantages of talent agglomeration, they should engage in diversified cooperation. Deepening industry-university-research collaborative cooperation with universities and research institutes, and fully relying on their high-quality research resources and talent reserve advantages, can enhance the efficiency and standard of clean-tech innovation.

Third, establish a reasonable penalty and reward mechanism. The government should maintain the sustainability of cooperation while stimulating the market, promoting green technology innovation from a long-run viewpoint. On the one hand, the government can cooperate with relevant enterprises and industry experts to conduct consultations and research to determine appropriate penalty intensities, reducing opportunistic behavior during enterprise cooperation. On the other hand, the government can establish a "blacklist" mechanism to make untrustworthy enterprises "transparent", thereby making corporate reputation an important foundation for cooperation and prompting enterprises to improve their own reputation and reduce contract breaches during cooperation.

Fourth, formulate a reasonable benefit distribution coefficient. When establishing cooperative relationships, enterprises should adhere to principles such as fairness and justice, symmetry between risk and return, and long-term orientation. They should communicate and negotiate by means such as quantifying inputs and using proportional methods to reach a benefit distribution plan satisfactory to both parties. At the same time, a contribution measurement mechanism can be established to evaluate management and operational contributions using indicators such as market share growth, number of patent applications, effectiveness of technological improvements, and improvements in team collaboration, thereby achieving fair benefit distribution.

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