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Simulating Environmental Innovation Behavior of Private Enterprise with Innovation Subsidies

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By reducing innovation costs, innovation subsidies can help private enterprises convert their production modes to green production. Based on method of computational experiment in social science, we construct a dynamic model for environmental innovation behaviors of private enterprises to simulate their evolution process in different market mechanisms, product competitions, and innovation subsidies and explore the impact of different subsidy modes on environmental technological innovation behaviors. The experimental results show that, under actions of multiagents, the combination of market subsidy and technology transformation subsidy can achieve the highest utilization efficiency of subsidy funds. However, when level of innovation technology is low, the innovation process should be subsidized at the same time to improve the competitiveness of innovative products. Besides, according to the level of innovation technology, flexible innovation subsidy combinations can be adopted to optimize subsidy in the different stages. The experimental results are of great significance for increasing efficiency of innovation subsidy funds and promoting green sustainable development of private enterprises.

1. Introduction

Due to the uncertainty and dual externalities of environmental technological innovation, for enterprises, the private return is less than the social return. Therefore, the environmental technological innovation levels of enterprises purely guided by market mechanism are bounded to be lower than the optimal level of society. Therefore, besides the two-standard demand-driven and technology-driven factors [1], the government's innovation policies have become an important driving force to stimulate the innovation vitality of enterprises [2]. It is a common policy for innovative countries to give some direct subsidies or tax incentives to technological innovation practices encouraging enterprises to develop new technology researches and developments [3, 4]. As a technology catching-up country, China government has also used R&D subsidy as a major policy to encourage enterprises innovate independently [5].

Compared with state-owned enterprises or foreign-funded enterprises with strong capital and technical strength,

the private enterprises, mainly small and medium-sized enterprises, have weak flexibility in choosing alternative production modes. Li Hongxia (2014) [6] constructed a green technology preference model for private enterprises with comparison of the average innovation intensities of private enterprise, state-owned enterprises, and foreign-funded enterprises. It was found that, due to high cost of machine renovation and technological innovation, the small-scale enterprises had weak impetus to change to green growth mode. Although the practices of European countries and the US have proved that environmental tax can promote enterprises to abandon the traditional production modes through continuous technological innovation and realize the switching to green production mode, tax may increases the burdens of private small and medium enterprises. It is even more unfavorable for private enterprises to adopt green innovation mode. Rather, the financial subsidy for green technological innovation can reduce the innovation cost of private enterprises, which is of great significance for the sustainable development of private enterprises.

By analyzing the data of the first national economic census and comparing the efficiencies of supports on direct subsidy and tax preference to enterprise innovation, Jiang Jing (2011) [7] found that the direct subsidy policy can significantly improve the R&D intensity of domestic enterprises. At the same time, based on panel data of 28 provinces in China, Fan Qi and Han Minchun (2011) [8] found that government innovation subsidy has a significant impact on improving national and regional independent innovations and the effect of subsidy on innovations in relatively developed regions is higher than that in relatively undeveloped regions. As for the impacts of different subsidy modes on innovations, Sheng Yanchao (2008) [9] used a three-stage game model to find that the mode of innovation subsidy on products is more effective than the mode of innovation subsidy on inputs under the government intervenes into the innovation system of technology alliance. However, through the study of asymmetric Cournot game model, Chen Lin and Zhu Weiping (2008) [10] found that innovation input subsidy, represented by "three fees for scientific research," did not significantly stimulate the growth of innovation output of the whole society; thus the effect of subsidy policies was somehow uncertain.

Although subsidy policies play an important role in technological innovation of enterprises, their actual performance is affected by many factors such as subsidy modes and external atmosphere. In fact, in addition to the external atmosphere impact, the heterogeneity in microlevel of enterprises also affects their attitudes towards environmental innovation technology. However, most of the existing studies are based on panel data to carry out empirical research or build a mathematical model with government and enterprises as the two sides of the game, which only analyze the relationship between government subsidies and technological innovation performance from the macrolevel. Enterprise environmental technological innovation is a complex process involving policy support, market mechanism, and product competition. Enterprise innovation decision-making depends on many internal and external factors, such as enterprise nature, capital situation, risk attitude, market expectation, and innovation policies. Especially, for private enterprises with small scale and flexible business model, macrolevel analysis is difficult to reveal the impact mechanism of policy changes on the microlevel of private enterprises, while grasping the motivation of environmental technological innovation in microlevel has a far-reaching significance for private enterprises to turn to green technology.

Based on empirical data, this paper constructs a dynamic simulation model of environmental technological innovation behaviors of private enterprises and uses social science computational experiments to dynamically simulate the interaction mechanism between environmental technological innovation behavior of private enterprises and external driving forces [11, 12]. The purpose of this paper is to clarify the motivation and influence mechanism of private enterprise's environmental technological innovation behaviors, provide microtheoretical support for environmental policy makers, promote private enterprises to consciously adopt environmental innovation technology, and adopt green sustainable development.

2. Model Construction

2.1. Scenario Description. The actual prototype of this model is a kind of private chemical enterprises. In the initial stage of the system, all enterprises adopt traditional technology and use an organic solvent in the production process. The production process is mature, cost is low, and the quality is good, but the VOC emission level is high. Although the emission reduction can be achieved by means of end-treatment, it is limited by technical means and the emission reduction effect is unsatisfactory. Environmental innovation technology uses a certain green solvent resulting from the low VOC emission, but the use of green solvent requires certain equipment input and production process reform. Because the production process is not yet mature, the production cost is higher and the product quality is not as good as traditional ones. But, through technological R&D and reformation, the production process can be continuously improved to reduce production costs.

The purpose of innovation subsidy is to induce enterprises to consciously choose environmental innovation technology. Sun Xiao Hua et al. (2014) [13] found that consumers' heterogeneity preference provides niche market for new products and plays an important role in industrial evolution. Therefore, the study of different policy efficiency needs to combine many complex self-correlation evolution mechanisms, such as enterprises competition and market choices. Because of the reasons that empirical methods are difficult to find comparative samples of different policy backgrounds, this paper adopts computing experimental method in social science, refers to some designed ideas of multiagent model constructed by Afaroui (2014) [14] and Liu Xiao Feng (2013) [15], and builds computational experimental model based on real prototype to simulate environmental technological innovation processes in complex environment of innovation subsidy, market mechanism, and enterprise competition. The proposed model emphasizes on dynamics and disequilibrium processes from an evolutionary perspective. It draws on basic principles of the evolutionary theory of technological change [16, 17].

The model mainly includes two kinds of subjects: production enterprises and consumers. Consumers choose products from different production enterprises based on their preferences, while enterprises can freely choose product technology routes according to their decision rules. In order to better observe the trajectories of enterprises' environmental technological innovation under different innovation subsidies, this model takes into account the complexity of the real system as far as possible with abstraction and simplification.

2.2. Basic Hypotheses. According to the scenario description in Section 2.1, the basic hypotheses of the system are as follows.

(1) T_1 represents the traditional technology of using organic solvents; T_2 represents the environmental innovation technology of using green solvents. The products produced by the two technologies are technology products T_1 and technology products T_2. According to Lancaster (1971) [18], each product is described by three attributes: price (related

to production costs), quality (representing technical performance), and VOC emissions (representing environment performance). The prices and qualities of the two products are different. The VOC emission per unit in the production process is also different. Moreover, after technological transformation, the lowest production cost, the highest product quality, and the minimum VOC emissions are also different.

(2) There are m manufacturing enterprises in the system, which are represented by enterprise number i ($i=1,2,\ldots m$). At the initial stage, all enterprises adopt technology T_1, but, because technology T_2 represents the direction of future development, according to the level of enterprise I's attention to technology T_2, a certain proportion of R&D input is applied to the early stage researches and developments of technology T_2. When certain conditions are met, enterprises may begin to adopt technology T_2 for formal production, but technology T_1 can coexist at the same time, until a certain condition is reached, and enterprises would abandon technology T_1. The adoption threshold of technology T_2 is different from the elimination threshold of technology T_1. In order to ensure stable total number of production enterprises in the system and maintain the free competition pattern, it is assumed that when the loss of production enterprises reaches a certain level, they will withdraw from the market, while new entrants will enter the market, regardless of the situation of enterprises obtaining loans and other external funds.

(3) There are n consumers in the system, which are represented by number j ($j=1,2,\ldots n$) of the consumer agent. Assuming that the product is a nondurable necessity, consumers need to buy one product every cycle. Because consumers do not know the details of production process, according to model of Zeppini et al. (2014) [19], consumers would mainly consider product price, performance, consumption habits, and product reputation in the diffusion of innovative products and have certain social imitation ability. Therefore, it is assumed that consumers choose products of different technologies according to product price and quality and different consumers may have different preferences for product price and quality. In addition, purchase decisions are influenced by other consumers. At the same time, considering that consumers have certain path dependence attributes under the influence of consumption habits, consumers would still opt to the original enterprise when the price and quality of the current production enterprises are within the tolerable range. Consumers have different tolerances for product price and quality.

(4) The product is a constant reward type. That is to say, the production efficiency will not increase with the expansion of production scale. Only by technological transformation can the production cost be reduced [20]. Therefore, it is assumed that product pricing is based on production cost, $P = C(1+\mu)$, where P is the product price, μ is the producer's satisfactory profit level (considering the producer's bounded rationality), and C is the production cost. We assume that all production enterprises have the same satisfactory profit level and can reflect the product price level through the production efficiency level of the production enterprises.

2.3. Rules of Agent's Behavior

2.3.1. Rules of Consumer Behavior.
The decision model of consumers is based on previous theoretical works on evolutionary demand [21]. Bounded rationality characteristic of customer is embodied by the comparison of specific threshold and imperfect information and some routines when they decide to purchase a product and to keep or leave original enterprise product [22]. Consumers consider both price and quality factors when choosing products and only when they reach the highest price affordability and the lowest quality requirements will they make out purchase decision. At the same time, different consumers may have different preferences for price and quality and are influenced by other consumers' choices [23]. Therefore, the effect function of consumers' choice of products is as follows:

$$
U_{k,i,t}^{j} = \left[(A - P_{k,i,t}) \times (Ms_{i,t-1} + \mu(0,0.1))^{\inf} \right]^{p_j^p}
$$
$$
\times \left[(X_{k,i,t} - B) \times (Ms_{i,t-1} + \mu(0,0.1))^{\inf} \right]^{p_j^x}
$$
(1)

Among them, j is the consumer number, k ($k=1,2,3,,$) is the product type (traditional technology products or environmental innovation technology products), i is the manufacturer number, and t is the simulation cycle. Assume that the total evolution cycles of the system are T; then each cycle is expressed by $t = 1, 2, 3$, respectively. A is the highest price that consumers can afford, B is the lowest quality requirement that consumers can accept, and $P_{k,i,t}$ and $X_{k,i,t}$ are the price and quality level of product k of enterprise i in t cycle, respectively. $Ms_{i,t-1}$ is the market share of enterprise i in the previous cycle and $u(0,0.1)$ is a random number between 0 and 0.1. It reflects the influence of other uncertain factors in the market and avoids the situation that the effect is zero when market share is empty. inf is interpreted as group psychology effect [24], reflecting consumers' imitation behavior; $P_{k,i,t}$ and $X_{k,i,t}$, respectively, reflect consumers' preferences for product price and quality; $p_j^p + p_j^x = 1$.

When choosing a product at the first time, consumers may determine their choice probability according to the effect function of each product and randomly select the product. In the follow-up cycle, consumers firstly observe the lowest price and the highest quality of all current enterprise products according to the principle of path dependence. When the quality-price ratio of the original producer's products is within the tolerance of consumers, the consumers would select the original production enterprise; otherwise, the product selection probability is determined according to its product effect function and the product is randomly selected.

2.3.2. Rules of Conduct for Manufacturing Enterprises.
The decision model of enterprises is based on the combination of economic theory and evolutionary theory and observation [14]: budget, mark-up pricing, R&D allocation, technology portfolio, and innovation process. Meanwhile, enterprises are bounded rationality [22]. They choose their technology portfolio by considering specific thresholds. According to the hypotheses, in the initial stage of the system, all enterprises

have the same scale and capital status. In each simulation cycle, enterprises gain profits from production sales and carry out technology transformation to improve product competitiveness. This model does not consider other ways to obtain funds, such as loans. The total disposable capital of the producer in each cycle is expressed as

$$BG_{i,t} = BG_{i,t-1} + \Pi_{i,t-1} - RD_{i,t-1} \tag{2a}$$

Among them, $\Pi_{i,t-1}$ and $RD_{i,t-1}$ are profit and R&D expenditure of enterprises in the last period.

For new technology T_2 adopters, additional technology switch cost (such as equipment investment, and staff training cost) is required.

$$BG_{i,t} = BG_{i,t-1} + \Pi_{i,t-1} - RD_{i,t-1} - SC_{i,t} \tag{2b}$$

SC is the related switching cost for the first adoption of technology T_2.

As mentioned before, product price can be deduced from production cost by applying a producer's satisfactory profit level μ (also called as mark-up rate) as $P = C(1+\mu)$. Therefore, the profit formula for each production cycle is as follows:

$$\Pi_{i,t} = \left(\mu \times C_{i,t} \times Q_{i,t} \right) - FC \tag{3}$$

Among them, μ is the producer's satisfactory profit level, $C_{i,t}$ is the production cost, $Q_{i,t}$ is the sales of products, and FC is the fixed cost.

(1) Entry/Exit Rules for Manufacturing Enterprises. When the disposable capital of a manufacturing enterprise is less than a certain level, the enterprise declares bankruptcy and withdraws from the market. At the same time, a new manufacturing enterprise enters the market as Van der and Brouillat (2015) [25] suggested. This is to maintain a constant number of enterprises over the whole time period. The technological route adopted by new production enterprises would imitate an existing enterprise in the system and the probability of choosing the imitated target is based on the market share of each enterprise. New enterprises imitate the technological route of target enterprises and the learning absorptive capacity is described as a random number between 0.8 and 1.2. This enables the new entrant to underperform or overperform in comparison with the imitated firm at a reasonable degree. Sensitive tests found that excessively low learning absorptive capacity would lead to exit from market faster than existing enterprises while excessively high setting would lead to outstanding performance. The price, quality, and *VOC* emission of products are multiplied or divided by random numbers (multiply positive index and divide negative index) on the basis of imitated enterprises' product indicators, so they can be lower or higher than those of the imitated enterprises. The initial disposable capital BG and fixed cost *FC* of the new enterprise are similar to those of other enterprises at the beginning. The switch cost *SC* of technology T2 and knowledge K would take the industries' averages.

(2) Technical Route Selection Rules for Manufacturing Enterprises. Innovation is an endogenous and uncertain process.

In fact, enterprises cannot know perfectly the results of their R&D activity. Therefore, the proposed model considers a stochastic process of innovation: most behavioral parameters are randomly drawn, the accumulation of knowledge that results from technology watch on T_2 is stochastic, etc. Firstly, each enterprise calculates its perception of technology T_2 maturity in a given cycle:

$$ADindex_{i,t}^{T_2} = K_{i,t-1} \times Ms_{t-1}^{T_2} \tag{4}$$

Ms^{T_2} represents the total market share of technology products T_2, and K represents the knowledge accumulation of technology T_2 acquired by enterprises through technology research and development. It is obvious that the possibility of adopting technology T_2 depends on the knowledge accumulation of technology T_2 and market diffusion of technology products T_2. When the enterprise considers the fact that the maturity of technology T_2 is greater than a certain degree (one of the attributes of the enterprise: technology T_2 adoption threshold), the enterprise checks whether there is enough disposable capital to support the new technology transformation. When $BG_{i,t} \geq SC_{i,t}$, the enterprise would formally adopt technology T_2 for production.

Adopting technology T_2 does not necessarily mean abandoning technology T_1. It is assumed that technologies T_1 and T_2 can coexist in the same enterprise. Whether or not to abandon technology T_1 depends on the proportion of product income of technology T_2 in total enterprise income:

$$Share_{i,t}^{T_2} = \frac{P_{i,t-1}^{T_2} \times Q_{i,t}^{T_2}}{\sum_{k=1}^{2} \left(P_{i,t-1}^{T_k} \times Q_{i,t}^{T_k} \right)} \tag{5}$$

When the proportion of technology T_2 reaches the threshold of enterprises abandoning technology T_1, enterprises will abandon technology T_1 and adopt technology T_2 exclusively. This threshold also reflects the enterprise's risk attitude towards technology T_2. The higher the threshold value is, the more conservative the enterprise is and the possibility of technology T_1 being abandoned is less and vice versa.

(3) Rules of Enterprise R&D Activities. Each enterprise improves the performance of products through R&D activities every cycle. The investment amount of R&D is as follows:

$$RD_{i,t} = \delta \times BG_{i,t} \tag{6}$$

Among them, δ is the investment ratio of R&D, on the premise that the enterprise's current disposable capital $BG_{i,t} > 0$.

The R&D investment of enterprises is proportionally applied to the R&D of technology T_1 and T_2:

$$RD_{i,t}^{T_1} = \delta_1 \times RD_{i,t} \tag{7a}$$

$$RD_{i,t}^{T_2} = \left(1 - \delta_1 \right) \times RD_{i,t} \tag{7b}$$

Among them, $\delta_1 \in [0, 1]$ for enterprises that only adopt technology T_2, $\delta_1 = 0$ for enterprises that only adopt

technology T_1, and $(1-\delta_1)$ represents enterprises' initial R&D and learning of technology T_2. That is, $RD_{i,t}^{T_2} = RDwatch_{i,t}$. Because the progress in R&D and learning of technology T_2 is uncertain and is related to funding, therefore, the knowledge accumulation needs to meet the following conditions:

$$1 - e^{-\alpha_w \times RDwatch_{i,t}} \geq u(0,1) \qquad (8)$$

where α_w is a model parameter, which determines the speed of knowledge accumulation for the current technology. u is evenly and randomly distributed in [0,1], reflecting the uncertainty of innovation activities in the real world. The closer to 1, the more difficult it is to satisfy condition (8). If the conditions are met, it means that R&D activities have achieved phased results, the knowledge accumulation of technology T_2 increases, and the switching cost of technology T_2 decreases. This is shown as

$$K_{i,t} = K_{i,t-1} + \alpha_k \times u(0,1) \times (K_{max} - K_{i,t-1}) \qquad (9a)$$

$$SC_{i,t} = SC_{i,t-1} - \alpha_{SC} \times u(0,1) \times (SC_{i-1} - SC_{min}) \qquad (9b)$$

α_k and α_{SC} are model parameters; K_{max} and SC_{min} are the extreme values of knowledge accumulation K and switching cost SC.

The process of technology transformation in production activities is similar to that of predevelopment and learning of T2 technology. The success of technology transformation depends on whether conditions are met or not:

$$1 - e^{-\alpha_1 \times RD_{k,i,t}} \geq u(0,1) \qquad (10)$$

Among them, α_1 represents the speed of technology transformation and u reflects the uncertainty of innovation activities. If the technology transformation is successful, the attributes of the product will be updated as

$$X_{k,i,t} = X_{k,i,t-1} + \beta_1 \times u(0,1) \times (X_{max}^k - X_{k,i,t-1}) \qquad (11a)$$

$$Cost_{k,i,t} = Cost_{k,i,t-1} + \beta_2 \times u(0,1) \\ \times (Cost_{max}^k - Cost_{k,i,t-1}) \qquad (11b)$$

$$Voc_{k,i,t} = Voc_{k,i,t-1} + \beta_3 \times u(0,1) \\ \times (Voc_{max}^k - Voc_{k,i,t-1}) \qquad (11c)$$

where u is a uniform random number, β_1 is the product quality, β_2 is the production cost, and β_3 is the improvement efficiency of VOC emission. X_{max}^k, $Cost_{max}^k$, and Voc_{max}^k are the extreme value that technology K can reach in all aspects of product performance. When the actual level of a given product property comes closer to the limit of what is achievable with specific technology, a given R&D expenditure will achieve less and less progress. The workflow of each production cycle is shown in Figure 1. This workflow reflects the basic principle of evolutionary theory of technological change, such as path-dependency, incremental versus radical innovation, and innovation risk, being cumulative and localized in a certain direction. Innovation is firm-specific which leads to technological diversity and heterogeneous performances. Consumer choices lead to heterogeneous demand, coevolution of firm strategies, and market structure.

2.4. Parameter Settings. To set the public parameters and individualized parameters for system simulation, we should consider the objective and realistic prototypes as far as possible. For the parameters that are difficult to quantify in reality (such as consumers' preference for product price and quality) [26], we would use the basic model (no innovation subsidy situation) to carry out "virtual-real linkage." By adjusting the parameters repeatedly, we observe the intermediate results and the final result to make the outcomes tally with the reality. After determining the parameters of the basic model, the policy parameters are introduced to observe the impact of the policies on the simulation results.

The main variables and their initial assignment rules in the system are shown in Table 1.

Empirically based parameters in Table 1 are determined basically in [14] and data from http://www.cefic.org/Facts-and-Figures/. Some parameters are adjusted according to the questionnaire survey of private enterprises in China (e.g., reduce initial disposable capital from 15 to 12). The questionnaire is related to enterprise environmental innovation behavior and innovation performance, including "R&D investment of enterprise environmental innovation," "factors affecting enterprise environmental innovation," and "economic performance of enterprise environmental innovation." Simulation training parameters are adjusted by the comparison result of benchmark model and empirical investigation. For example, although most enterprises agree that environmental innovation is the best way to overcome current environmental barriers and improve their competitiveness, only about 10% of enterprises with strong technical strength are willing to carry out environmental innovation considering a long-term interest. The reason of low adoption comes from immature technology, inadequate product competitiveness of environmental technology, and high expenditure of additional equipment investment, personnel training and market development costs, and so on. Therefore, related parameters are trained to coincide with this empirical result.

3. Simulation Experiment and Result Analysis

Based on the situation of without innovation subsidy, this model mainly analyses the effects of three subsidy policies on environmental technological innovation behavior of private enterprises: process subsidy, technology transformation subsidy, and market subsidy of environmental innovation products. In order to compare the effects of each subsidy policy, this paper designs the following scenarios for comparative experiments:

O: no innovation subsidy

P: subsidies for enterprise in the process of environmental technological innovation.

T: subsidies for enterprises to adopt environmental innovation technology when requiring switching costs, such as investment in new equipment

M: price subsidies for environmental innovative products

TABLE 1: Main variables and initial assignment rules.

Variables/parameters	Implication	Assignment	Assignment rules
m	Number of enterprises	10	Fixed
n	Number of consumers	200	Fixed
A/B	Consumers' maximum affordable Price/minimum Acceptable quality	6/20	Simulation training
p^p	Consumer price preference	[0.1,0.9]	Consumer random
inf	Consumer conformity effect	0.05	Simulation training
Tol	Consumer tolerance	[0.8,1.2]	Simulation training
$X_{max}^1/Cost_{min}^1/Voc_{min}^1$	Technology product T1 maximum Quality/minimum Cost/minimum VOC emission	100/0.4/2	Based on the empirical analysis
$X_{max}^2/Cost_{min}^2/Voc_{min}^2$	Technology product T2 maximum Quality/minimum Cost/minimum VOC emission	100/0.4/0	Based on the empirical analysis
$X_0^1/Cost_0^1/Voc_0^1$	Technology product T1 Initial quality/initial cost/initial VOC emission	100/0.5/23	Based on the empirical analysis
$X_0^2/Cost_0^2/Voc_0^2$	Technology product T2 Initial quality/initial cost/initial VOC emission	32/3/0.05	Based on the empirical analysis
B_0	Initial disposable capital of enterprise	12	Based on the empirical analysis
μ	Satisfied profit level	0.5	Based on the empirical analysis
FC	Fixed cost	2	Based on the empirical analysis
Ad_{min}	Threshold of adoption technology T2	[0,2]	Enterprise random
SC	Initial switch cost	20	Based on the empirical analysis
$Aband_{min}$	Threshold for abandoning technology T1	[0.5,1]	Enterprise random
δ	R&D investment ratio	0.2	Based on the empirical analysis
δ_1	R&D investment ratio of technology T1	[0,1]	Enterprise random
α_w	Knowledge speed	0.2	Simulation training
d_1	Speed of technology transformation	0.25	Simulation training
K_{max}	Maximum cumulative value of knowledge	1	Based on the empirical analysis
SC_{min}	Minimum switching cost	10	Based on the empirical analysis
$\beta_1/\beta_2/\beta_3$	Product quality/production cost/ improvement efficiency in VOC emissions	0.05/0.08/0.05	Simulation training

PT, PTM, PM, and TM: the combination subsidy schemes of the above three subsidies accordingly.

According to the above definition, we simulate the processes of enterprise environmental technological innovation in different scenarios and further analyze the efficiencies and effects of various innovation subsidy schemes.

3.1. Path Analysis of Enterprise Environmental Technological Innovation on Single Subsidy Scenario. In the scenario P, on the basis of the basic model, the government implements a 1:1 matching approach to subsidize the R&D investment of enterprises for environmental technological innovation. Therefore, the subsidy of enterprises i in the cycle T is described as follows:

$$Sub_{i,t}^{T_2} = (1 - \delta_1) \times RD_{i,t} \qquad (12a)$$

In the scenario T, the government subsidizes switching costs of enterprises to adopt environmental innovation technology. Therefore, the subsidy of enterprises i in the cycle T is described as follows:

$$Sub_{i,t} = SC_{i,t} \qquad (12b)$$

In the scenario M, the government subsidizes environmental innovative products in markets. After subsidization, the market average price of technology products T2 is equal to the market average price of technology products T1. Therefore, the subsidy of enterprises i in the cycle T is described as follows:

$$Sub_{i,t} = (P_{2,i,t} - avg(P_{1,i,t})) \times Q_{i,t}^{T2} \qquad (12c)$$

We set the total simulation cycle number to 300 and repeat simulation 50 times in the different scenarios and
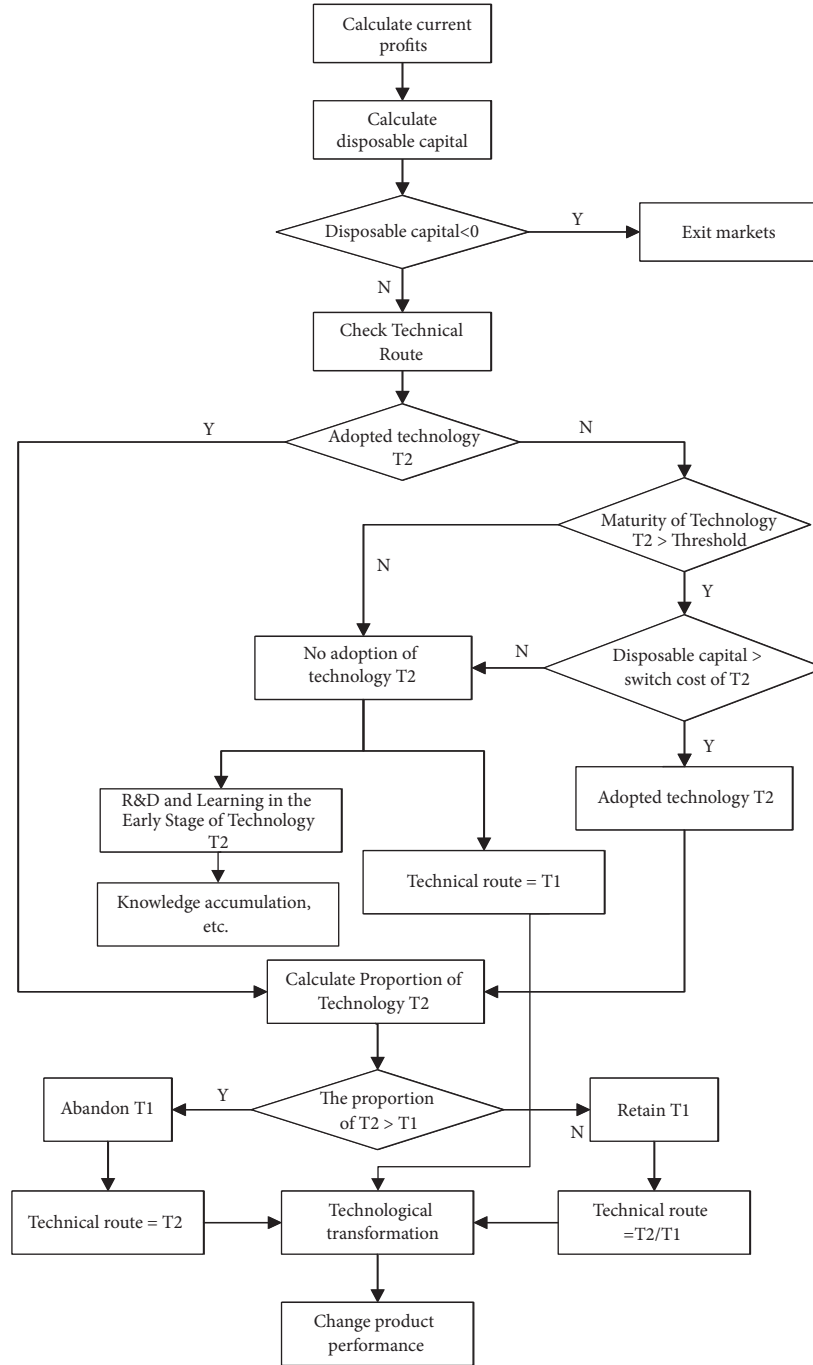
Figure 1: The workflow of each production cycle.

then take the average of each simulation results. In a single subsidy scenario, the adoption of environmental innovation technology by enterprises in each cycle is shown in Figure 2.

Figure 2 shows that different subsidy policies have different impacts on the technological route of enterprises: (1) compared with the P scenario and the O scenario, the number of enterprises adopting combination technology has increased significantly, but no enterprises adopt technology T2 completely; (2) in the scenario T, from 120th cycle on, some enterprises have completely switched to technology T2, and after 150 cycles although most enterprises still retain technology T1, they have partially or completely adopted technology T2; (3) in the scenario M, although some enterprises begin to completely switch to technology T2 after 120 cycles, 80% of them still do not adopt technology T2. From the perspective of enterprise technology route only, subsidy policy in the scenario T is the most effective mode to diffuse environmental innovation technology.

(a) Evolution of enterprise technology route under scenario O.

(b) Evolution of enterprise technology route under scenario P.

(c) Evolution of enterprise technology route under scenario T.

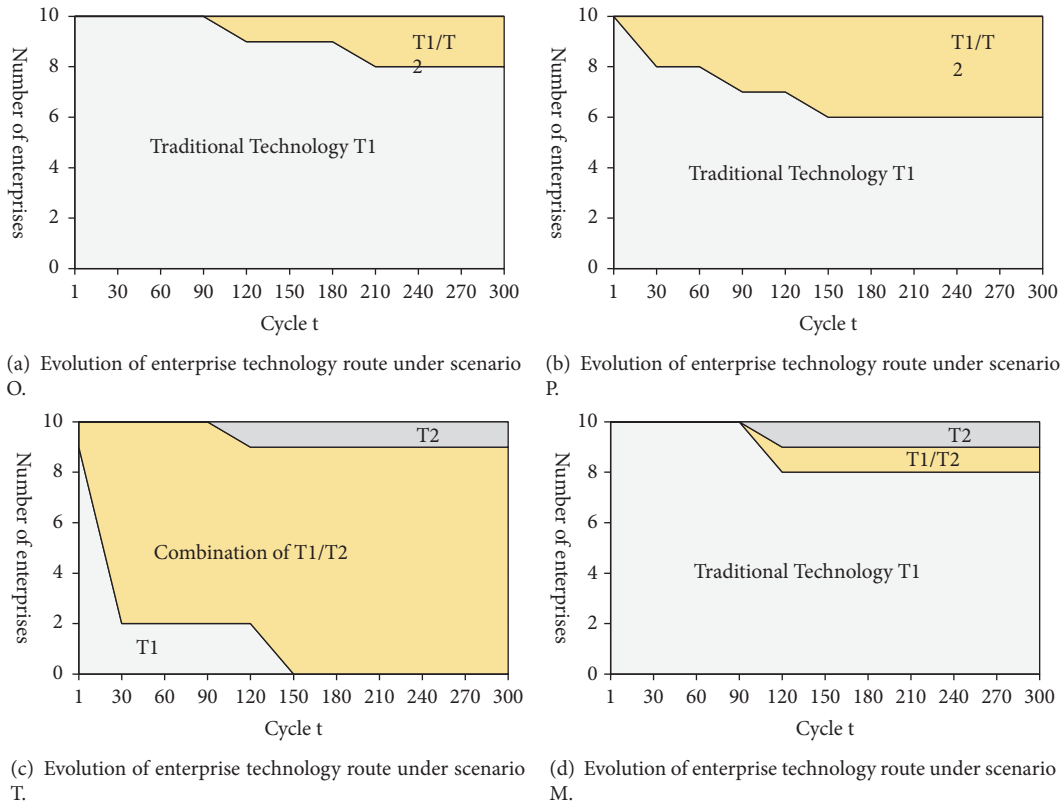(d) Evolution of enterprise technology route under scenario M.

FIGURE 2: Evolution of enterprise technology route under single subsidy policy scenarios.

The market share and competitiveness of products T2 in the different scenarios are shown in Figure 3.

As can be seen from Figure 3(a), although there are still a large number of enterprises using only technology T1 in the scenario M of Figure 2(d), the market share of technology products T2 is still larger than those of other scenarios. In the scenario T, although all enterprises adopt environmental innovation technology, the lack of competitiveness in product T2 regarding quality and price (Figure 3(b)) leads to a low market share (lower than P and M scenarios) because the government only subsidized the technology switching cost of enterprises. Thus, from Figure 2(c), most enterprises still retain technology T1. In the scenario P, with the support of enterprise innovation process subsidy, it can be seen from Figure 3(b) that the competitiveness of technology products T2 is rising faster. Therefore, although the adoption rate of technology T2 in Figure 2(b) is low, the market share is higher than that in the scenario T. Overall, the three subsidy policies all have positive impacts on the increase of market share of technology products T2, but the overall competitiveness of products T2 is less than that of products T1 (less than 50). The market diffusion effect of products T2 in cycle 300 is not ideal; even with the highest market share in the scenario M, the diffusion effect in cycle 300 is only about 12%. The reason is in the scenario M; although the price of products T2 has been subsidized, the competitiveness of products T2 is weak because the quality of products T2 is not as good as that of technology products T1. In

the scenario P, although the performance of products T2 improves rapidly, the actual adoption rate of technology T2 is low due to the lack of sufficient technology transformation funds. In the scenario T, although technology transformation is subsidized, it is difficult for technology products T2 to win the market due to their slow performance improvement and weak competitiveness.

3.2. Path Analysis of Enterprise Environmental Technological Innovation on Combination Subsidies Scenario. In the single subsidy scenario, the market diffusion effect of technology products T2 is not ideal. Therefore, various combinations subsidies are considered: PT, PTM, PM, and TM. In the combination subsidy scenario, the innovation subsidy obtained by enterprises in each cycle is accumulated with individual subsidy schemes in each scenario. The adoption of environmental innovation technology by enterprises in each cycle is shown in Figure 4.

From Figure 4, it can be seen that the proportion of adopting technology T2 in the combination subsidy scenarios is higher than those in the single subsidy scenarios. Especially in the scenario PTM, all enterprises adopt technology T2 partially or completely after 30 cycles, and 70% of them adopt technology T2 completely. In the scenario TM, although 10% of enterprises did not adopt technology T2 in the 300th cycle, 60% of enterprises completely adopt technology T2. In the scenario PM, the number of enterprises adopting technology T2 is also significantly higher than that in the scenario P or

(a) Evolution of market share of product T2.

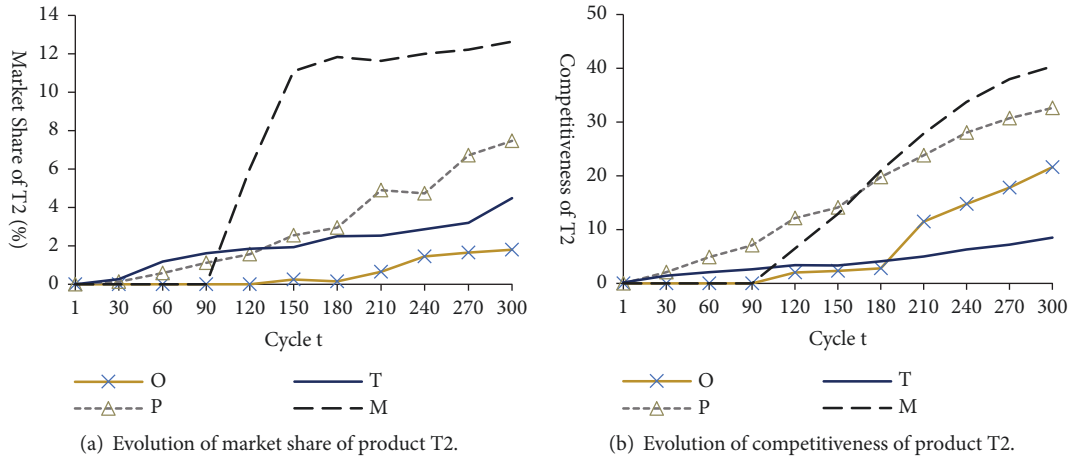

(b) Evolution of competitiveness of product T2.

FIGURE 3: Evolution of market share and competitiveness of product T2 under single subsidy scenario. *Note.* Product competitiveness is calculated according to consumer effect function (1). The calculation results are standardized with the maximum value of current consumer effect as 100. The competitiveness of product T2 is the average value of all standardized products T2 in the market.

(a) Evolution of enterprise technology route under scenario PT.

(b) Evolution of enterprise technology route under scenario PTM.

(c) Evolution of enterprise technology route under scenario PM.

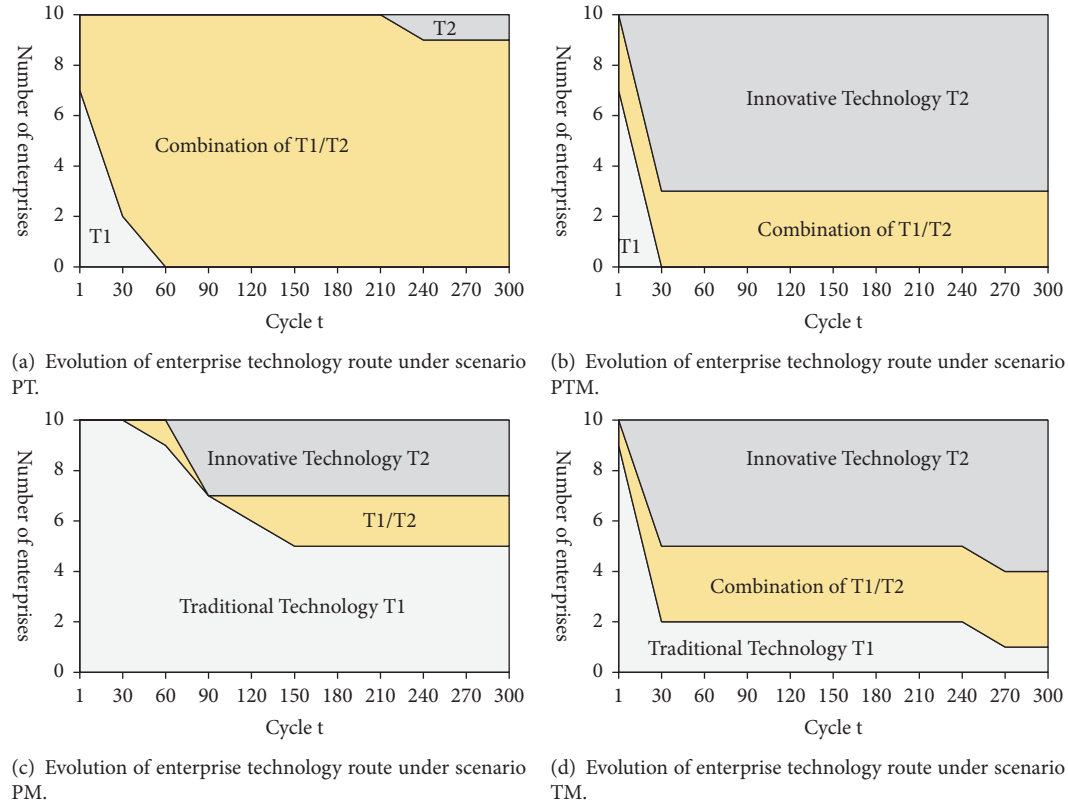(d) Evolution of enterprise technology route under scenario TM.

FIGURE 4: Evolution of enterprise technology route under combination subsidy scenarios.

M alone. In the scenario PT, although all enterprises begin to adopt technology T2 partly or completely after 60 cycles, enterprises which adopt technology T2 completely only appear after the 240th cycle and are only composed of 10%. Compared with other combination policies, the adoption rate of enterprise environmental innovation technology in the scenario PT is the lowest.

The market share and competitiveness of products T2 in the different combination subsidies scenarios are shown in Figure 5.

Figure 5(a) shows that the market share of technology products T2 is ordered as PTM > TM > PM > PT, which corresponds to the technological route adopted by enterprises in the combination subsidy policies in Figure 4. However,

(a) Evolution of market share of products T2.

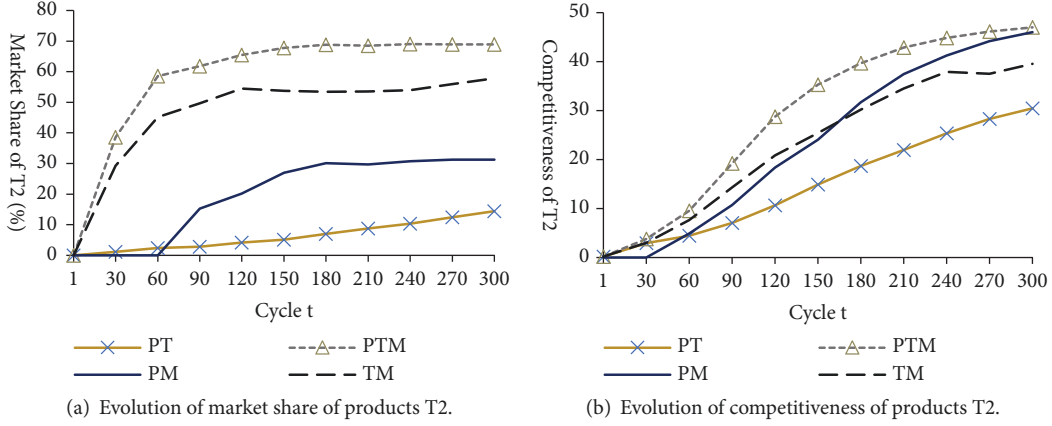(b) Evolution of competitiveness of products T2.

FIGURE 5: Evolution of market share and competitiveness of products T2 under combination subsidy scenarios.

as shown in Figure 5(b), the competitiveness of technology products T2 in the 300th cycle is ordered as PTM > PM > TM > PT; that is to say, the subsidies are cancelled after 300 cycles, because the competitiveness of technology products T2 in the scenario PM is greater than that in the scenario TM. The market share of technology products T2 will be PM > TM, which is due to the fact that PM subsidy mode in technology T2 innovation process is more beneficial for the improvement of product competitiveness than that of TM subsidy mode. In addition, because TM subsidy mode helps more enterprises to adopt technology T2 in advance by subsidizing enterprises to complete technology transformation, the market share of technology products T2 is higher than that of PM subsidy mode. In the scenario PT, although the innovation process subsidy benefits the competitiveness of products T2, the competitiveness of products T2 is still weaker than that of products T1. In the absence of market subsidy incentives, products T2 would have the lowest market share.

It can be seen that the combination of M policy (market subsidies for technological products T2), P policy (subsidies for enterprise environmental innovation process), and T policy (technology transformation subsidies for enterprises) can better promote the diffusion of environmental innovation technology.

3.3. Analysis of Innovation Subsidy Efficiency in Different Scenarios. From the above analysis, it can be seen that different subsidy policies have different effects on the adoption of technology T2 and the diffusion of products T2. Assume that subsidies needed to increase a unit share of products T2 in the different scenarios are described as follows:

$$U\_subsidy_t^{T_2} = \frac{T\_subsidy_t^{T_2}}{Sup_t^{T_2}} \qquad (13)$$

$T\_subsidy_t^{T_2}$ is the total investment of innovation subsidy in the cycle T; $Sup_t^{T_2}$, based on the market share of products T2 in each cycle under no innovation subsidy, is the growth rate of market share of products T2 in different scenarios. $U\_subsidy_t^{T_2}$ is the subsidy needed to increase the unit share
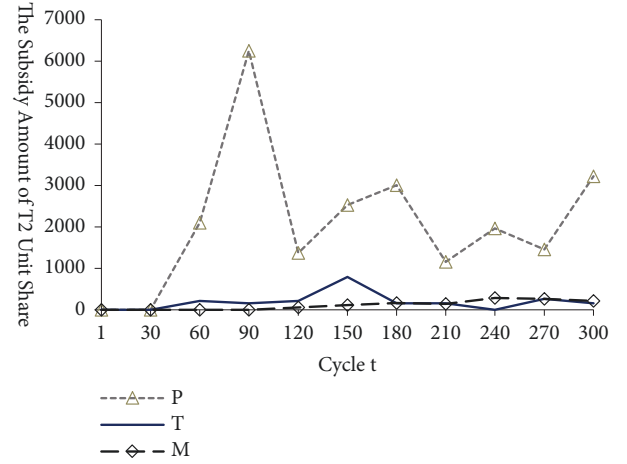

FIGURE 6: Evolution of innovation subsidy efficiency under single subsidy scenarios.

of products T2. Without considering the indirect effects of subsidy, such as improvement of the competitiveness of products t2, the reciprocal of innovation subsidy efficiency can be regarded as the work efficiency of innovation subsidy in different scenarios. The reciprocal of innovation subsidy efficiency in the single subsidy scenario is shown in Figure 6.

As can be seen from Figure 6, in the single subsidy scenario, the efficiency of innovation subsidy in the scenarios M and T is the highest, while that in the scenario P is the lowest.

The reciprocal of innovation subsidy efficiency in the combination subsidy scenario is shown in Figure 7.

As shown in Figure 7, in the combination subsidy scenario, the efficiency of innovation subsidy is the highest in the scenario TM and the lowest in the scenario PTM at the 300th cycle. Figures 4 and 5 show that TM subsidy effect is only second to PTM. Although PTM subsidy effect is the best, the efficiency of capital utilization is low; especially after the 180th cycle, it becomes the lowest. We may consider optimizing the PTM subsidy by stages. PTM can improve the
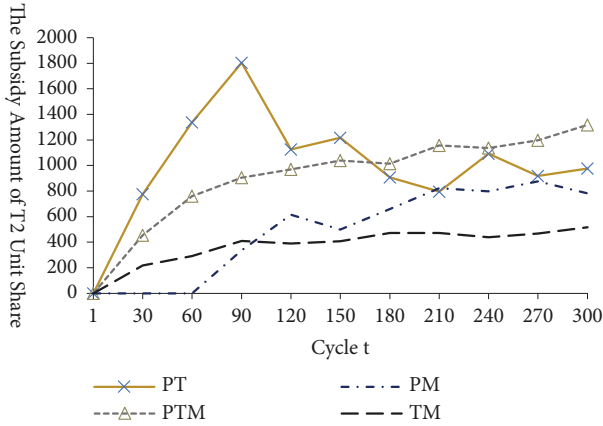
FIGURE 7: Evolution of innovation subsidy efficiency under combination subsidy scenarios.

competitiveness of products T2 in the early stage and improve the efficiency of innovation subsidy in the later stage.

4. Conclusions

Taking the environmental technology innovation process of a private enterprise in a chemical industry as an example, through social science computational experiment method, this paper constructs a model of environmental technological innovation of private enterprises and simulates the processes of environmental technological innovation of enterprises in the different innovation subsidies scenarios. The proposed model can help to closely observe the dynamic innovation process and technology transformation process from a microperspective.

As we discussed, under the increasingly severe pressure of environment problem, more and more enterprises begin to pay attention to environmental innovation technology. Enterprises' original motivation of carrying out environmental innovation is the improvement of product competitiveness to obtain higher profits. However, the survey of enterprises' willingness to adopt environmental innovation technology found that although most enterprises agree that environmental innovation is the best way to overcome current environmental barriers and improve their competitiveness, only about 10% of enterprises with strong technical strength are willing to carry out environmental innovation considering a long-term interest. The reason of low adoption comes from immature technology, inadequate product competitiveness of environmental technology, and high expenditure of additional equipment investment, personnel training and market development costs, and so on. The price subsidy of environmental innovative products directly improves the price competitiveness of environmental innovative products. The process subsidy of environmental innovation helps to improve the performance of all dimensions of innovative products. Subsidizing the conversion costs of enterprises when they adopt environmental innovative technologies can help enterprises break through the bottleneck of capital during new conversion. Therefore, these subsidy modes are conducive

to the improvement of environmental innovation adoption. The proposed model reveals the influence mechanism of different subsidy modes on enterprises' environmental innovation behavior and the limitation of single subsidy mode from the microperspective. For example, when government provides market price subsidy for environmental innovative products, the market for environmental innovative products is growing, and more enterprises are encouraged to increase the R&D investment and actual production of environmental innovative technology. However, high cost of environmental technology conversion and the difficulty of private enterprise financing have become the bottleneck of transformation and upgrading of most private SMEs. Therefore, the combination subsidy would be the better way to improve the effectiveness of subsidy.

Simulation experiments under different scenarios show that efficiency of subsidized funds is related to the level of innovation technology. When innovation technology is not mature enough, policy should focus on innovation process subsidy to improve innovation technology as far as possible. On the contrary, the combination of product market subsidy and innovation technology conversion subsidy would achieve the highest efficiency of capital utilization. Therefore, based on different levels of innovation technology, flexible combination of innovative subsidy modes can be applied in different stages of technology development to optimize the efficiency and effect of subsidy funds. For example, in the early stage of innovation technology promotion, PTM subsidy portfolio policy can be used to improve the market competitiveness of T2 technology products. When innovation technology becomes more mature, TM subsidy portfolio should be used to help enterprises complete the replacement of new and old technologies and increase the market share of innovative products.

In practice, in order to ensure the flow and efficiency of the use of subsidized funds, more flexible specific subsidy modes can be adopted. For example, the combination of R&D input plus deduction policy and reward for innovative achievements can be employed as innovation process subsides, green financial financing mode for innovation technology transformation can be used as technology conversion subsidy, and the combination of consumption guidance and market subsidy can be applied as environmental innovation product subsidy, and so on.

While designing and analyzing the model, several interesting ideas arise which nevertheless are neglected for the sake of clarity and simplicity. Some of these ideas deserve further development as they might develop into fertile new lines of research: (1) the model assumes that the scale and capital conditions of enterprises are the same at the initial stage of the system, without considering the different enterprise scales. (2) The model does not further discuss the multistage combination of subsidy policy, nor does it discuss the evolution of enterprises' environmental technological innovation behaviors after innovation subsidy policy. (3) Consumers' purchasing decisions only involve product prices, qualities, consumption habits, and conformity effects, without considering their preferences for product environmental attributes.

Data Availability

The experimental data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

Acknowledgments

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